TAMPERE UNIVERSITY OF TECHNOLOGY

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CONCEPT DEVELOPMENT OF A FRONT FRAME FOR PRODUCTION DRILL RIGS

Master of Science Thesis

Examiner: Professor Asko Riitahuhta
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ABSTRACT

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Product development is an important area of operations in today’s business world. Continuous development of technologies and changes in regulations force companies to develop their products and services constantly to achieve and maintain competitiveness.

This thesis deals with underground mining products, in more detail with Sandvik’s production drill rigs (long-hole drilling rigs). The goal of the thesis is divided into two parts. The first goal is to investigate whether some characteristics could be added to Sandvik’s frame version of production drill rigs. The characteristics under examination are the possibility to get the drill close to the side wall in a vertical position and the ability to drill inclined fans without that a driller must leave the cabin of canopy. The second goal is to redesign the front frame of the frame model to improve its maintainability and drilling stability.

The development process of this thesis bases on Pahl et al.’s and Ulrich’s & Eppinger’s product design methodologies. The design process begins from planning and proceeds via task clarification to concept design. After three iteration rounds in the concept design phase, a new proposal for the front frame is presented.

The proposed front frame for the frame model is redesigned from the current horseshoe shape. Maintainability is improved by widening the side beams from 150 mm to 225 mm and by changing their profile so that the hoses can be located outside the closed beams. Drilling stability, instead, is improved by adding jack beams to the front carrier frame in front of the front wheels. The front frame is reshaped to create the space for the jack beams.

Getting the drill close to the wall by adding an extra part to the structure makes the front frame approximately 850 mm longer. Allowing inclined fans by adding an extra part under the boom module, for one’s part, makes the rig approximately 100 mm higher. Both features also cause troubles in stability. Because of the increased outer dimensions and stability problems, adding these features to the frame model is discovered to be impossible to realize.

As a conclusion, it can be summarized that the first goal of adding new features to the frame model was found impossible but the second goal of improving the current front frame of the frame model was fulfilled. As the changes to the structure are fairly easy to realize, the result can be considered successful.

TIIVISTELMÄ

TAMPEREEN TEKNILLINEN YLIOPISTO
Konetekniikan koulutusohjelma
MYLLÄRI, AINO-MAIJA: Tuotannon porauslaitteiden etukehikon konseptikehitys
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Avainsanat: etukehikko, konsepti, laite, pitkäreikäporaus, tuotannon poraus, tuotekehitys.

Tuotekehityksellä on tärkeä rooli nykyaikaisessa yritysmaailmassa. Teknologian kehityksen ja määräysten muuttumisen takia tuotteiden ja palveluiden jatkuva kehittäminen on elinarvoisen tärkeää kilpailukyvyn saavuttamisessa ja ylläpitämisessä.

Tämän diplomityön aihe käsittelee maanalaisia kaivoslaitteita, tarkemmin sanottuna Sandvikin tuotannon porauslaitteita (pitkäreikäporauslaitteita). Työn tavoite jakautuu kahteen osaa. Ensimmäinen tavoite on tutkia, voidaanko tietyt ominaisuudet lisätä Sandvikin tuotannonporauslaitteiden kehikko-versioon. Tutkittavat ominaisuudet ovat kyky saada porakone pystysuorassa asennossa lähelle tunnelin seinää sekä porata vinoja viuhkoja siten, että porarin ei tarvitse poistua hytistä tai suojakatoksen alta. Työn toinen tavoite on parantaa kehikko-mallin etukehikon huollettavuutta ja laitteen porauksen aikaista vakautta.

Työn kehitysprosessi pohjautuu Pahl et al.:in ja Ulrichin & Eppingerin tuotekehitysmenetelmiin. Prosessi alkaa suunnitteluvaiheella, josta se etenee tehtävän kehittely- vaiheen kautta konseptisuunnittelu- vaiheeseen. Konseptisuunnittelu-vaiheessa käydään läpi kolme iteraatiokierrosta, joiden jälkeen esitellään ehdotus uudesta etukehikosta.

Ehdotettu uusi etukehikko on suunniteltu nykyisestä hevosenkenkämallista. Huollettavuutta on parannettu leventämällä sivupalkkeja 150 mm:stä 225 mm:iin. Lisäksi palkkien profiilia on muutettu siten, että letkut voidaan sijoittaa umpinaisten palkkien ulkopuolelle. Porauksen aikaista vakautta on puolestaan parannettu lisäämällä maatuet laitteen etualustaan eturenkaiden eteen. Maatukien vaatiman tilan takia etukehikon muotoa jouduttiin hieman muuttamaan.

Poran lähelle seinää saavan rakenteen lisääminen laitteeseen pidentää etukehikkoa noin 850 mm. Vinot viuhkat mahdollistava lisäpala puomimoduulin alla puolestaan kasvattaa laitteen korkeutta noin 100 mm:llä. Molemmat lisätyt rakenteet aiheuttavat ongelmia myös laitteen vakaudessa. Kasvaneiden ulkomittojen ja vakausongelmien vuoksi tavoitteena olleita ominaisuuksia ei voida lisätä kehikko-malliin.

Johtopäätöksenä voidaan tiivistää, että työn ensimmäinen tavoite lisätä uusia ominaisuuksia kehikko-malliin todettiin mahdottomaksi toteuttaa. Sen sijaan työn toinen tavoite, nykyisen kehikko-mallin parantaminen, pystyttiin täyttämään. Koska muutokset rakenteeseen ovat suhteellisen helppoja toteuttaa, tulosta voidaan pitää onnistuneena.

PREFACE

This thesis has been an interesting project for me. I am grateful to Sandvik Mining for giving me the opportunity to accomplish the thesis in their Tampere plant. I would like to thank Juha Piipponen, Sami Järventausta, Martti Kansola and Tero Yli-Hannuksela for their support and valuable advices during this project. In addition, thank you for all the co-workers, who have helped me with my thesis.

A word of thanks also belongs to professor Asko Riitahuhta from Tampere University of Technology for his instruction.

During the thesis I was allowed to familiarize myself with genuine environment of production drill rigs in Pyhäsalmi Mine. The visit opened my eyes for the demands the rigs face underground. Thank you to Kari Kumpumäki for an interesting and educational interview and to Hannu Pynnönen for organizing the visit to Pyhäsalmi.

Finally, I want to express my gratitude to my family, and particularly to my beloved husband Ville, for supporting and encouraging me during all the years of studying.

Tampere, 22 May 2012

Aino-Maija Mylläri

TABLE OF CONTENTS

ABBREVIATIONS

C	Cabin
DL	Drilling Longhole
DTH	Down The Hole
E	Energy
EFS	Extra Feed Swing
FFT	Field Failure Rate
ITH	In The Hole
S	Signal
V&V	Verification and Validation

1. INTRODUCTION

1.1. Mining

Mining has a major significance in providing of usable resources in the world. It has had a large impact on the development of the human civilization since the Stone Age. Besides offering raw materials for industries, mining has brought wealth to mineral-rich countries. (Hartman & Mutmansky 2002)

Hartman & Mutmansky (2002, p. 3) define the term mining as "…the activity, occupation, and industry concerned with the extraction of minerals". Instead, mining engineering indicates to exploiting engineering principles in mining (Hartman & Mutmansky 2002, p. 3).

This Master of Science Thesis deals with mining industry, in more detail with production drill rigs. Production drill rigs are used for drilling long holes and for that reason they are also called long-hole drilling rigs. The holes from production drilling are filled in with explosives and blasted to dislodge the ore-rich material from the soil or rock (Hartman & Mutmansky 2002). Ore is defined in Hartman's and Mutmansky's book *Introductory Mining Engineering* (2002, p. 3) as "… a mineral deposit that has sufficient utility and value to be mined at a profit". The term mineral in the previous definition indicates to natural inorganic substances (Hartman & Mutmansky 2002, p. 3).

The goal of this thesis is to develop top-hammer long-hole drilling products. Mining principles and techniques used in long-hole drilling are introduced in more detail in a theory part in chapter 2.

1.2. Company presentation

This thesis is done in co-operation with Sandvik Mining. Sandvik Mining belongs to the Sandvik Group's international high-technology group. The three main values of Sandvik are fair play, team spirit and open mind. The strategy of the Group is based on the good overall performance. According to Sandvik's official web page "The Group occupies a world-leading position in selected areas". (Sandvik)

Sandvik Mining supplies different applications and services for mining industry. The offering includes products for example for drilling, hauling and crushing. In 2011 Sandvik Mining had 13,200 employees. The amount is approximately a fourth of the personnel of the whole Group. The sales of Sandvik Mining in 2011 were over 32 billion Swedish Krona (about 3.6 billion Euro according to the rate of The Money converter.com on April 18, 2012), which is more than a third of the Sandvik Group's sales. (Sandvik; Sandvik Mining)

1.3. The goal and proceeding of the thesis

This thesis deals with production drill rigs (long-hole drilling rigs). Two same sized rigs with different front parts and characteristics are under investigation. The goal of this thesis is to investigate, whether two positive features (drilling inclined fans and getting the drill close to the wall in the vertical position) of the classic model could be added to the frame version. Another goal is to redesign the front frame of the frame model (DL421) to improve its functionality. The result is aimed to be presented as a technically credible concept. The models and features under investment are introduced in more detail in sub-section 4.1.

In chapter 2, a theoretical background is presented. To be able to design practical and functional devises, knowledge of the working principle of the device is vital. For that reason the principles of top-hammer and long-hole drilling are introduced. Methods used in long-hole drilling are described as well. The development process of this thesis is based on Pahl et al.'s and Ulrich's and Eppinger's product development methodologies (Pahl et al. 2007; Ulrich & Eppinger 2008). As the goal of this thesis is to create a technically credible concept solution, the product development methodologies introduced cover only the concept development phase. After distinct introductions, the two product development methodologies are united and the applicable methodology being used in this thesis is described. In addition, it is vital to ensure that the customer needs and technical specifications are fulfilled. A theory of verification and validation is presented for this purpose in chapter 2. To create a technically believable concept, rough strength calculations are needed. The basic equations for the calculations are given at the end of chapter 2.

Chapter 3 includes the planning phase of the project. First, the topic is defined and then the preliminary knowledge is gathered to a mission statement.

Chapter 4 covers the task clarification. The input of this phase is the mission statement. In this chapter the current products are presented, competitor analysis is performed and a check list is gone through. All the requirements found at the mentioned three sections are finally gathered to the requirements list.

In chapter 5 the concept development is carried out by starting from the requirements list. First, the requirements list is abstracted. On the grounds of the abstracted requirements list, a function structure is created. Working principles are searched in a Tuplatiimi meeting and several working structures are combined from the found working principles. A preliminary evaluation is performed by a selection chart and the concept proposals that pass the preliminary evaluation are evaluated in more detail. Parts of the mentioned steps are replicated in the iteration rounds. Finally, after three iteration rounds, the chosen concept is modeled and rough calculations are made and the verification is executed.

Chapter 6 provides conclusions of the executed process.

2. THEORETICAL BACKGROUND

This chapter introduces the theoretical background of the thesis. The theory part consists of four main categories: principles and techniques of long-hole drilling (sub-sections 2.1.-2.2), design methodologies (sub-sections 2.3.-2.5.), a theory of verification and validation (sub-section 2.6.) and basic strength calculation equations (sub-section 2.7.).

2.1. Drilling

Drilling is the first operation of an extracting process (Hartman & Mutmansky 2002, p. 15). According to Tamrock (1997) drilling is premised on crushing the rock and causing cracks to the rock. Drilling is divided into three categories based on the operating principle: to top-hammer (TH) drilling, rotary percussive drilling and Down-The-Hole (DTH) drilling (also known as In-The-Hole drilling, ITH) (Tamrock 1997).

Different kinds of drills are used for creating tunnels and drifts, as well as for long-hole drilling and short-hole drilling (Tamrock 1997). The Northern Miner defines a drift to be “A horizontal underground opening that follows along the length of a vein or rock formation ... “ Long-hole drilling is called production drilling when it is used to drill ore.

This thesis concentrates on TH long-hole drill rigs, and therefore only the structure, functions and methods of the TH long-hole drilling are introduced. Further information about the other drilling categories and techniques can be found for example from sources Tamrock (1997) and Hartman & Mutmansky (2002).

2.1.1. Top-hammer drilling

According to Hartman and Mutmansky main components of a TH drill are a drill, drill rods and a bit. The drill is defined as “the mechanical device … that converts energy from its original source … into rotational and/or percussive energy to penetrate the rock”. The function of the drill rod, which is “also called a steel, stem, or pipe”, is to convey the rotational and/or percussive energy. The energy finally conducts to the bit, which “attacks the rock with rotational and/or percussive action”. (Hartman & Mutmansky 2002, p. 124-125). A rough structure of a TH drill can be seen in Figure 2.1. in the next page.

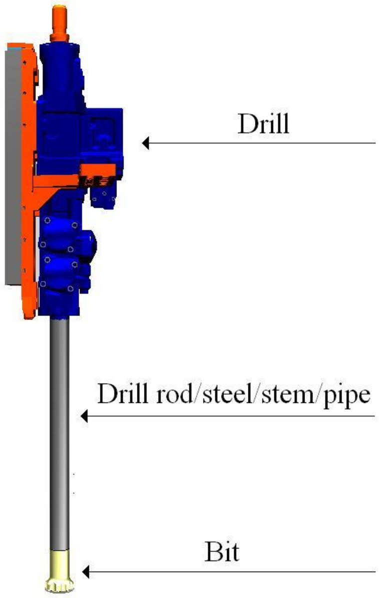


Figure 2.1. *Main components of a TH drill (Figure modified from: Unigraphics NX).*

Functions of a top-hammer drill are percussion, feed, rotation and flushing. The purpose of percussion is to break the rock by striking the bit to the bottom of the hole whereas rotation changes the place the buttons of the bit hit the rock. The percussion is directed to the drill, and for that reason the drilling devise is called a top-hammer. Feed is required to maintain the contact with the bit and the bottom of the hole. The fourth function, flushing, flushes the hole bringing rock cuttings out, at the same time as it chills the bit. (Tamrock 1997)

2.1.2. Long-hole drilling

Long-hole drilling is a capable method for many applications that require several drill rods. Long-hole drill rigs have a wide range of hole sizes, typically varying from 51 mm to 127 mm; in special occasions the hole size can be bigger or smaller. (Tamrock 1997)

When drilling long holes, the accuracy of the drill is remarkably important. The significance of hole alignment is emphasized, as the error at the end of a hole grows as a function of the hole length. Drilling errors can also be caused by deviation, incorrect set-up of a rig and/or inaccurate length of a hole. The lack of accuracy can cause unwanted blasting results and ore losses and for that reason the stability and rigidity of the rig is vital. (Tamrock 1997) Some factors causing inaccuracy are presented in Figure 2.2. in the next page.

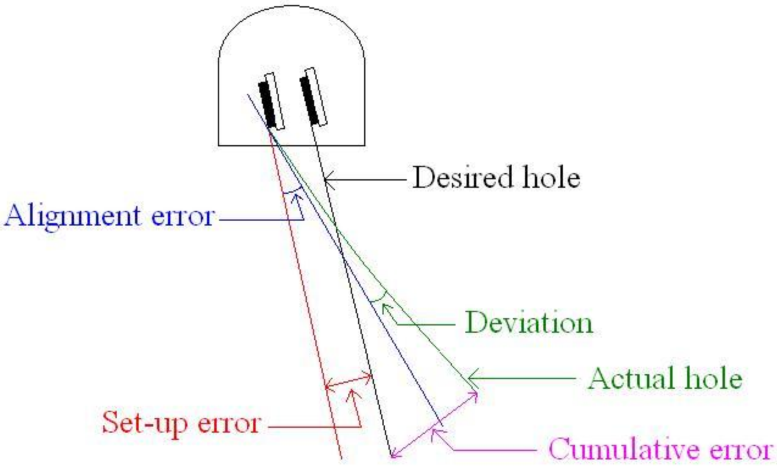


Figure 2.2. *Factors that cause inaccuracy in long-hole drilling (Figure reproduced from: Tamrock 1997, p. 63).*

The environment in underground mines is humid and dusty. This environment combined with metallic acids sets high demands for corrosion tolerance of long-hole drilling rigs. Wear must also be taken into consideration because of ore dust. (Tamrock 1997, p. 92)

2.2. Methods for long-hole drilling

According to Tamrock (1997) long-hole drilling is typically conducted by applying one of the following methods: 1) sublevel stoping, 2) underground benching, 3) sublevel caving or 4) block caving. Common for all these methods is that there are several mining sections and the ore is collected “from the bottom of the stope” (Tamrock 1997, p. 99). The four methods are introduced in the sub-sections below.

2.2.1. Sublevel stoping

Sublevel stoping method is used in mines with “vertical or deeply dipping orebody” (Tamrock 1997, p. 105). The mine consists of several sublevels that are connected by a stope and a ramp/raise (see Figure 2.4.). Drilling is performed from the drifts of the sublevels. A usual drift size at the sublevels is 3.5 m × 3.5 m to 4.5 m × 4.5 m. The sublevels are typically located vertically 10 – 60 m apart from each other. Because of the structure of a mine of this method, waste rock must be competent to ensure the stability of the mine. (Tamrock 1997) A cut-through picture of sublevel stoping is presented in Figure 2.3. in the next page.

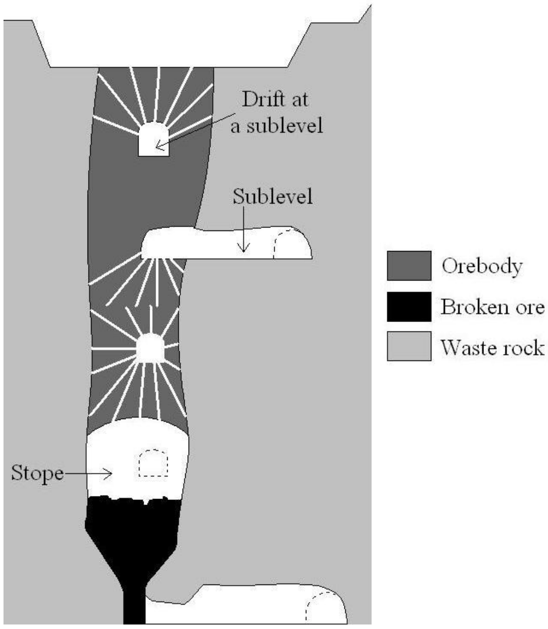


Figure 2.3. *A cut-through of sublevel stoping (Figure reproduced from: Tamrock 1997, p. 106)*

Planning is a crucial part of sublevel stoping as the mine needs a large amount of development, and correcting possible mistakes is troublesome or even impossible. Pillars of ore that are left to support the mine require exact planning as well. (Hartman & Mutmansky 2002, p. 345; Tamrock 1997).

As already mentioned, drilling is performed from the drifts. Fans or/and parallel holes are drilled to form vertical slices to the drift. A typical hole diameter is 51 – 125 mm but sometimes even a diameter of 250 mm is used. The lengths and angles of the holes are determined by the shape of the ore and the location of the drift. The holes are typically a maximum of 60 m long but with the biggest diameter (250 mm) the length can be 90 m. The fans are drilled from 1.8 m to 5 m apart from each other advancing backwards. This distance between the fans is called a burden. (Hartman & Mutmansky 2002, p. 346; Tamrock 1997) Figure 2.4. shows burden marks on a drift wall.

Figure 2.4. *Burden marks on the drift wall in Pyhäsalmi Mine (Figure taken by Juha Hokka).*

Drilling can be executed simultaneously at different sublevels. After drilling, the fans are charged and blasted to the bottom of the stope starting from the lowest sublevel. The broken ore is hauled at the haulage level. When all the ore of the stope is hauled away the stope must often be filled to form a pillar. (Tamrock 1997) Figure 2.5. shows an open stope in Pyhäsalmi Mine. Pyhäsalmi Mine uses both sublevel and bench stoping. Only sublevel stoping is introduced in this thesis. (Inmet Mining Corporation)

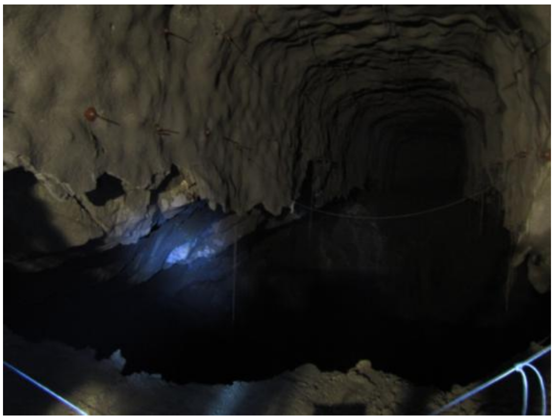


Figure 2.5. *An open stope in Pyhäsalmi Mine. In this drift only underhand holes* are drilled and blasted (Figure taken by Juha Hokka).*

* According to Hartman and Mutmansky 2002 (p. 269) "Underhand: Advancing in a downward direction".

In sublevel stoping, accuracy of drilling is important. Inaccuracy not only causes ore losses but in the worst case may also lead to the prohibition of use of the stope. Stability of the rig is a key thing in assuring the accuracy. (Tamrock 1997)

Sublevel stoping method has both positive and negative characteristics. Advantages and disadvantages according to Tamrock (1997) are gathered to Table 2.1.

Table 2.1. *Advantages and disadvantages of sublevel stoping (Tamrock 1997).*

Advantages	Disadvantages
• Drilling, blasting and loading can be executed separately • Usable in different sized operations • Rather inexpensive • Fairly small ore loss • Can be mechanized and automated • Easy to ventilate • Safe	• Not suitable for selective mining • Collecting the ore, which is left to the walls after blasting, is impossible • Boulders are common • Filling may be time-taking and expensive • Unexpected caving can sometimes occur • Starting costs are high and the payback time is long

2.2.2. Underground benching

Underground benching is a largely similar method with sublevel stoping. It is used in mines where the orebody is large and homogeneous and the excavated materials are in a solid form. (Tamrock 1997, p. 108)

Like sublevel stoping, underground benching "starts from the bottom of the orebody and proceeds upwards" (Tamrock 1997, p. 108). No fans are used in underground benching but parallel holes are drilled and blasted (see Figure 2.6.). Typically, the holes are blasted at their whole length but blasting only half of it is possible as well. (Tamrock 1997) The basic idea of underground benching is shown in Figure 2.6.

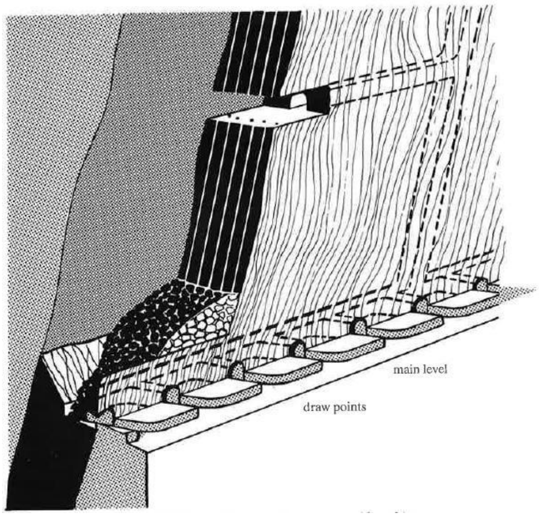


Figure 2.6. *Underground benching (Tamrock 1997, p. 110, Figure 2-8).*

In underground benching, drilling can be conducted either with a top-hammer or a DTH drilling rig. A typical hole size is 102 – 127 mm but hole diameters up to 165 mm are also used. The holes are normally 30 – 60 m long. Because of the lengths and the diameters of the holes, accuracy of the rig plays a crucial role in underground benching. (Tamrock 1997)

The advantages and disadvantages of underground benching according to Tamrock (1997) are gathered to Table 2.2.

Table 2.2. *Advantages and disadvantages of underground benching (Tamrock 1997).*

Advantages	Disadvantages
• Need for development smaller than for example in sublevel stoping • Cost-efficient (in right conditions) • Great amount of output • Can be mechanized	• Challenges in deviation and dilution* • Charging becomes more time-taking and more difficult as drilling proceeds

* According to The Northern Miner dilution indicates to “Rock that is, by necessity, removed along with the ore in the mining process, subsequently lowering the grade of the ore”.

2.2.3. Sublevel caving

Sublevel caving method can be exploited in mines with steeply dipping orebodies. The structure of the mine is based on several sublevels that lie vertically 8 – 35 m apart from each other. Sublevels consist of drifts and crosscuts. (Hartman & Mutmansky 2002; Tamrock 1997) According to The Northern Miner a crosscut indicates to “A horizontal opening driven from a shaft and (or near) right angles to the strike of a vein or other orebody”. A shaft, in turn, is “A vertical or inclined excavation in rock for the purpose of providing access to an orebody. Usually equipped with a hoist at the top, which lowers and raises a conveyance for handling workers and materials” (The Northern Miner). For safety reasons, excavated ore must be competent. Waste rock, instead, needs to be fairly weak to enable its caving into free space that is born when the ore is hauled away. (Hartman & Mutmansky 2002; Tamrock 1997)

Development and excavation in the sublevel caving method proceed downwards starting from the highest sublevel. The drifts are drilled to the orebody and as much as 20 % of the ore can be reached during development. Development is possible in several lower levels at the same time as excavation is conducted at the upper levels (see Figure 2.8.). Excavation is performed by drilling overhand fans and then blasting the ore to the drift. (Tamrock 1997) According to Hartman and Mutmansky 2002 (p. 269) “Overhand: Advancing in an upward direction”. A typical hole size in production drilling is 51 – 115 mm in diameter. The blasted ore is then loaded and hauled. A similar process is done at the lower levels after particular time. (Tamrock 1997) Figure 2.7. illustrates the structure of a mine and the proceeding order in the sublevel caving method.

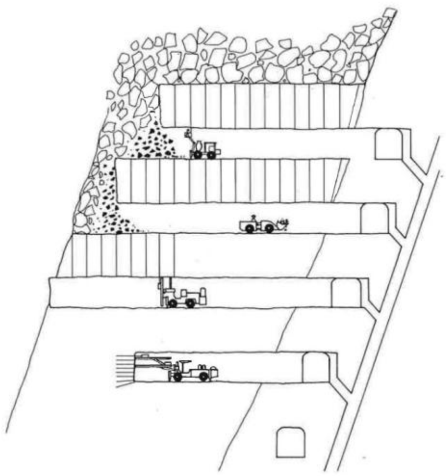


Figure 2.7. *A cut-through picture of sublevel caving (Tamrock 1997, p. 111, Figure 2-9).*

A challenge in sublevel caving is to define the point at which loading is stopped. The goal is to load as much ore as possible and at the same time avoid dilution. (Tamrock 1997, p. 114)

Like the methods presented above, sublevel caving has advantages and disadvantages. They are gathered to Table 2.3. in the next page (Tamrock 1997).

Table 2.3. *Advantages and disadvantages of sublevel caving (Tamrock 1997).*

Advantages	Disadvantages
• Simultaneous operations in different sublevels are possible • Mechanized equipment can be exploited well • Safe (when properly controlled)	• Need for strict monitoring • Equipment must be frequently moved • Ventilation can cause troubles • Unsafe (when not properly controlled) • Caving often affects the conditions on the ground

2.2.4. Block caving

According to Tamrock (1997, p. 117) “Block caving can be used to mine large massive orebodies under favourable geological conditions. The orebody must be steeply dipping and fairly thick and break easily into suitable fragments.” This method is based on undercutting large blocks and caving of the ore. Block caving is the most economical underground mining method when it is applied in the right way in the right environment. (Tamrock 1997)

According to Tamrock (1997, p. 119) mining can proceed in three different ways:

- (Fairly) square areas are undercut under the whole block. Drawing is realized evenly so that the upper surface of the ore stays horizontal.
- Panels across the orebody are undercut, which causes an inclined ore-waste border.
- Undercut area is not clearly divided.

The undercut opening area causes caving in the ore. After undercutting, only loading and haulage is needed. The broken ore is drawn away, which induces caving in the ore above already broken ore. (Hartman & Mutmansky 2002, p. 420; Tamrock 1997)

There are two main variants in block caving: traditional block caving and trackless block caving. Traditional block caving exploits the gravity, grizzly drifts and finger raises in the transportation of the ore, whereas trackless block caving demands more mechanization, loading drifts and a haulage level. (Tamrock 1997) The traditional and trackless versions are shown in Figures 2.8. in the next page.

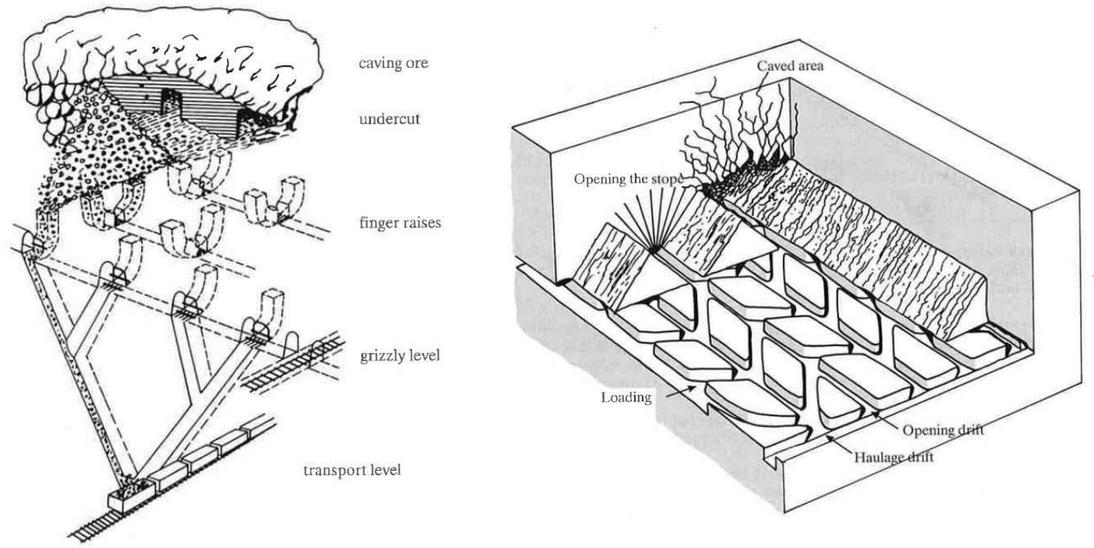


Figure 2.8. *Left: A traditional version of block caving (Tamrock 1997, p. 117, Figure 2-13). Right: A trackless version of block caving (Tamrock 1997, p. 118, Figure 2-14).*

Research of cavability has a significant role in block caving. Ore must have suitable hardness and fracture properties. Loading also demands strict control. Drawpoints and draw rate must be properly defined to avoid unwanted pressure. (Hartman & Mutmansky 2002, p. 421; Tamrock 1997)

Table 2.4. lists the advantages and disadvantages of block caving according to Tamrock (1997).

Table 2.4. *Advantages and disadvantages of block caving (Tamrock 1997).*

Advantages	Disadvantages
• High output and low relative costs (when properly planned) • Yield of pure ore even 70 – 80 % (when properly monitored)	• Inflexible • Precise control of draw rate needed • Mistakes cause ore losses and surprising caving • Can be used in large-scale operations only, with stable ore boundaries • Heavy support needed • A large amount of oversized rock

2.2.5. Implication of the methods for the thesis

The purpose of having introduced the methods was to give the reader a basic understanding of how the rigs are used and what kinds of features are important in TH mining processes. The methods set restrictions, preconditions and demands for the rigs. The most important factors are presented below.

One of the most important features that can be concluded from the method presentations is the need for good accuracy of drilling. Accuracy of drilling affects productivity and safety of a mine. Accuracy can be improved with stable drilling equipment. Thus, good stability of a top-hammer rig is an important feature.

According to the method introductions above, mechanization can be well exploited in long hole drilling. This means that there is seldom a need to leave the cabin or canopy, which opens possibilities for several applications.

Finally, in sublevel caving method rigs must be frequently moved. This emphasizes the importance of tramming position and thus restricts the outer dimensions of the rig.

2.3. Pahl et al.'s methodology

Pahl et al.'s methodology presents methods for product development. Product planning and designing methods are presented in the book *Engineering Design: A Systematic Approach (2007)*. The goal of the methodology is to help design leaders and designers in their projects by offering suitable design methods. (Pahl et al. 2007, p. 24) In Pahl et al.'s book the term designer is used for both development engineers and design engineers. (Pahl et al. 2007, p. 1)

According to Pahl et al. a design process consists of four phases; 1) planning and task clarification, 2) conceptual design, 3) embodiment design and 4) detail design (Pahl et al. 2007, p. 129). It is important to understand the iterative nature of the product development process. Although Pahl et al. present the process as a chain of phases, returning to the previous phases (iteration) is common as the knowledge increases. (Pahl et al. 2007)

The goal of this thesis is to create a technically credible concept of the product and for that reason only phases 1 (Planning and task clarification) and 2 (Conceptual design) are introduced.

2.3.1. Phase 1: Planning and task clarification

In the planning and task clarification phase a project is carefully defined before moving on to an actual development process. The planning phase can be executed for instance by planning departments, clients or consultancies, whereas the task clarification is completed by designers of a company. Planning is discussed in Pahl et al.'s book as a pre-design activity. Planning and task clarification are closely related, even if they were performed by separate parties. (Pahl et al. 2007)

The planning and task clarification phase begins with market and company analyses, on the grounds of which product ideas are created and evaluated. After the product proposal, the project is defined. This first phase of product development process ends in creating a requirements list that includes the specifications of the product. (Pahl et al. 2007, p. 130)

The requirements list consists of demands and wishes of the features the product must or should fulfill. Demands are those that must be fulfilled and wishes those that should be paid attention to. Demands and wishes can be either quantitative or qualitative, although the quantitative form is preferable. (Pahl et al. 2007) According to Roth et al. (1975) the wishes should be divided into three classes of importance: minor, medium and major (see Pahl et al. 2007, p. 147). A modified format of the requirements list is illustrated in Table 2.5.

Table 2.5. *A recommended format of a requirements list (Table modified from: Pahl et al. 2007, pp. 148 and 154).*

User		**Requirements list** **Project, product**	**Issued on** **Page:**
Dates of changes	Demand (D)/ Wish (W)	Requirements	Responsible
		Replaces issue of	

Identifying requirements is often the most difficult task during the planning and task clarification phase. The requirements are set on the grounds of customer needs, checklists and scenarios, after which they are arranged logically. The requirements list is a dynamic document that must be updated during the development process. (Pahl et al. 2007)

2.3.2. Phase 2: Conceptual design

The preliminary knowledge of the conceptual design phase is the requirements list created at the previous phase. There are seven steps in the conceptual design phase: 2.1) abstracting, 2.2) establishing function structures, 2.3) searching for working principles, 2.4) combining working structures, 2.5) selecting suitable combinations, 2.6) firming up into principle solution variants and 2.7) evaluating variants. (Pahl et al. 2007, p. 160)

Step 2.1. Abstracting

The first step (2.1) of conceptual design is abstracting, which can be considered as a synonym for generalization. The goal of abstracting is to find the central problem of the product under development. During the abstracting phase the requirements list is condensed into one sentence. First, personal opinions and irrelevant requirements are ejected from the requirements list. Then, quantitative requirements are converted into qualitative ones. At the end of abstracting, the requirements that are remaining are generalized and the problem is presented irrespective of any solution. The final output of abstracting is one sentence that expresses the crux of the problem. (Pahl et al. 2007)

Step 2.2. Establishing function structures

Once the central problem has been clarified, the functions of the product are defined (step 2.2). The main function can be copied or derived from the output of abstracting. Inputs and outputs of the main function are marked by means of energy (E), material and signal (S) flows. The flows are named to describe the form of the flow. (Pahl et al. 2007, pp. 169-170) An example of a main function is shown in Figure 2.9.

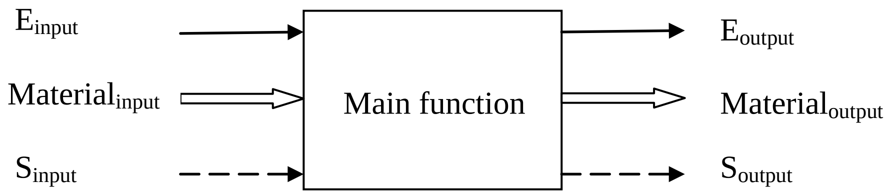


Figure 2.9. *An example of a main function (Figure created based on: Pahl et al 2007, p. 175).*

The main function is then divided to subfunctions and the subfunctions are arranged to form one or several function structures. Energy, material and signal flows are marked and named in the structure. (Pahl et al. 2007) An example of a function structure is illustrated in Figure 2.10.

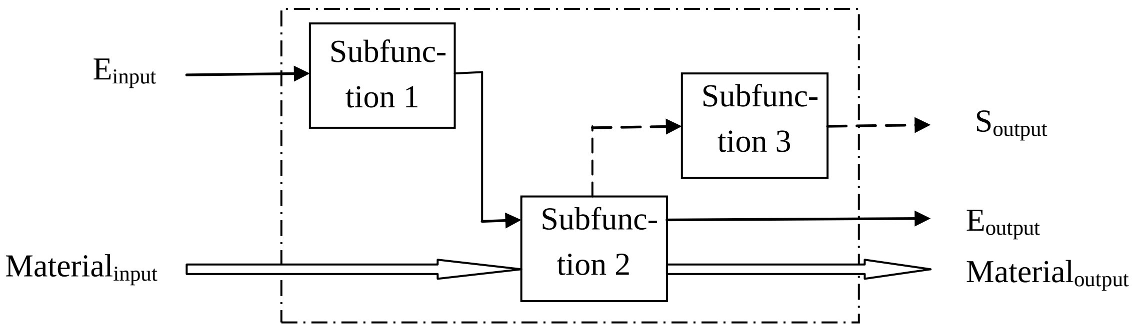


Figure 2.10. *An example of a function structure (Figure created based on: Pahl et al. 2007, p. 175).*

Step 2.3. Searching for working principles

Once the subfunctions have been determined, it is time to search for working principles (step 2.3). Several solutions for each subfunction are to be discovered in this step. Different solution finding methods can be exploited in this task (Pahl et al. 2007, p. 181). According to Pahl et al. for example the following methods are especially useful: (Pahl et al. 2007)

- nature analysis
- analysis of known technical systems
- literature search
- analogies
- Brainstorming
- Method 635
- Gallery Method
- Delphi Method
- Synectics
- classification schemes

According to Koller (1976/1985), Roth (1994/1996) and VDI-Richtlinie 2222 Blatt 2 (1982) design catalogues are also worth exploiting (see Pahl et al. 2007, pp. 181-182). Method selected to be used in this thesis is introduced in more detail in section 2.5. The results of the search are collected to a classification scheme (Pahl et al. 2007, p. 184). Pahl et al. recommend that a format that Zwicky (1966-1971) calls “a morphological matrix” is used (see Pahl et al. 2007, p. 104). In the morphological matrix subfunctions are located in the rows on the left and the related solutions are presented in the columns corresponding to the row. Illustrative pictures are desirable. (Pahl et al. 2007, p. 182-83) An example of a morphological matrix is shown in Table 2.6.

Table 2.6. *An example of a morphological matrix (Table created based on: Pahl et al. 2007, pp. 182-183)*

Subfunctions \ Solutions		1	2	3
A	Subfunction_1	Solution_{11}	Solution_{12}	Solution_{13}
B	Subfunction_2	Solution_{21}	Solution_{22}	Solution_{23}

Step 2.4. Combining working structures

The fourth step of conceptual design is combining working structures (step 2.4). During this step, realistic concept alternatives from the found solutions are formed. The alternatives must fulfill the requirements list and subfunctions must be compatible. Only the best alternatives are to be chosen for more detailed examination. (Pahl et al. 2007)

Step 2.5. Selecting suitable combinations

Selecting suitable combinations (step 2.5) can be performed by creating a selection chart or a compatibility matrix for the solutions of the subfunctions. Solutions are analyzed and decisions, whether they are applicable or not, are made. (Pahl et al. 2007) Examples of the selection chart and the compatibility chart are shown in Appendixes 1 and 2.

Step 2.6. Firming up into principle solution variants

The second last step of concept development is firming up into principle solution variants (step 2.6). Over this step the most promising combinations are described in more detail to enable the last step, evaluation. Firmed up solution variants include for instance estimated calculations, crude sketches, market research, analysis and physical models. (Pahl et al. 2007)

Step 2.7. Evaluating variants

As mentioned above, the last step of concept development is evaluating variants (step 2.7). Pahl et al. recommend that this step is executed through an eight-step procedure based on Cost–Benefit Analysis (Zangemeister 1970) and Guideline VDI 2225 (VDI-Richtlinie 2225 1977). First, evaluation criteria must be established. The primary source of criteria is the requirements list. In addition, using a checklist helps designers to take all aspects of the product into account. An appropriate number of criteria is 15–30 and all the criteria must be in a positive form. Cost–Benefit Analysis calls evaluation criteria objective criteria and suggests the criteria to be gathered to an objective tree, in which the criteria are presented hierarchically (see figure 2.14.). (Pahl et al. 2007)

Pahl et al. (2007, p. 193) present the following main headings, from which the evaluation criteria are recommended to be derived:

- assembly
- costs
- embodiment
- ergonomics
- function
- maintenance
- operation
- production
- quality control
- recycling
- safety
- transport
- working principle

After the evaluation criteria are established, the criteria are weighted. According to Pahl et al., an exact weighting in the concept development phase is not recommended, but only the most important requirements are given a weighting. (Pahl et al. 2007, p. 194) Figure 2.11., however, illustrates an objective tree, in which all the criteria are weighted. In Figure 2.11. O_x indicates an object criterion and numbers show the weightings of the criteria. An objective tree can also be horizontal, like in Pahl et al.'s (p. 223) example. The first numbers declare the shares of the criteria at certain level and the second numbers tell the absolute shares.

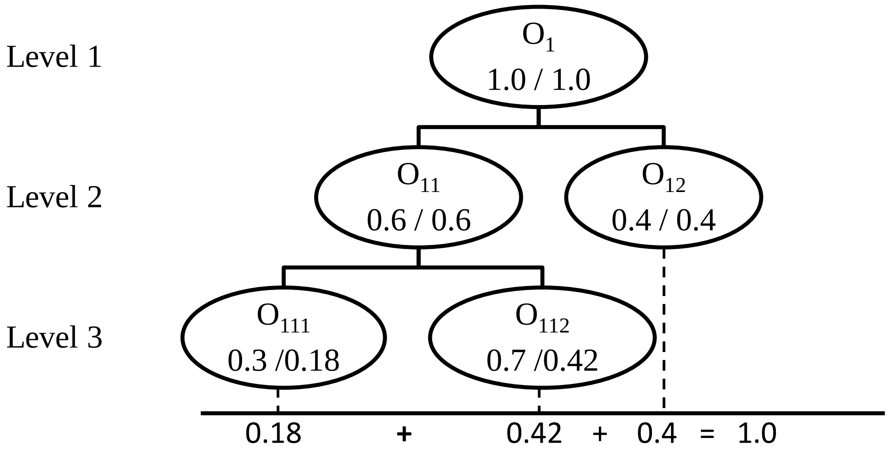


Figure 2.11. *An example of a weighted objective tree (Figure created based on: Zangemeister 1970, see Pahl et al. 2007, p. 112).*

Next the parameters for the criteria are set and values are determined. The values in Cost-Benefit Analysis are set between 0 and 10, whereas in VDI 2225 they are set between 0 and 4. The table of the ranges and an example of parameter magnitudes are presented in Appendix 3. The values for the left-standing concept alternatives are estimated and gathered to an evaluation chart. When all values are set, the overall value can be counted simply by summing up the values and the weighted values of each concept. Summing is, however, reliable only if the criteria have no strong dependence on each other. (Pahl et al. 2007) An example of an evaluation chart is presented in Table 2.7.

Table 2.7. *An example of an evaluation chart (Table created based on: Pahl et al. 2007, p. 117). No. indicates number, We. weighting, Magn. magnitude and We. value weighted value. The sums of the values and the weighted values are counted up in the bottom row.*

	Evaluation criteria		Objective parameters		Variant V_1			Variant V_2		
No.	Name	We.	Name	Unit	Magn.	Value	We. value	Magn.	Value	We. value
1										
2										
…										
		$\sum=1$				$\sum=$	$\sum=$		$\sum=$	$\sum=$

The sixth step in the evaluation of the concepts is to compare the variants. The received sums are compared with a theoretically ideal value. Those, whose value is under 60 % of the ideal one, can be excluded from embodiment design. If the value is over 80 % of an ideal one and the variant has no significant weaknesses it can be developed further without any improvement. The rest of the variants need to be improved if they are to be moved to the embodiment design phase. (Pahl et al. 2007)

After the comparison, it is important to identify uncertainties and errors of the evaluation. Uncertainties and errors can be caused for instance by subjectivity, unsuitable, interdependent or missing criteria, or a lack of information. (Pahl et al. 2007)

Finally, value profiles of some of the concept variants are created to detect possible weak spots. The profiles do not need to be done for every variant, but for those with high ratings and even scores. Balanced profiles are more preferable than unbalanced. For that reason it may be reasonable to choose a lower rated and balanced concept instead of a high rated and unbalanced variant. The profiles can be illustrated for example by graphs that show the weightings and the values of the criteria. (Pahl et al. 2007) An example of two value profiles can be seen in Figure 2.12. in the next page.

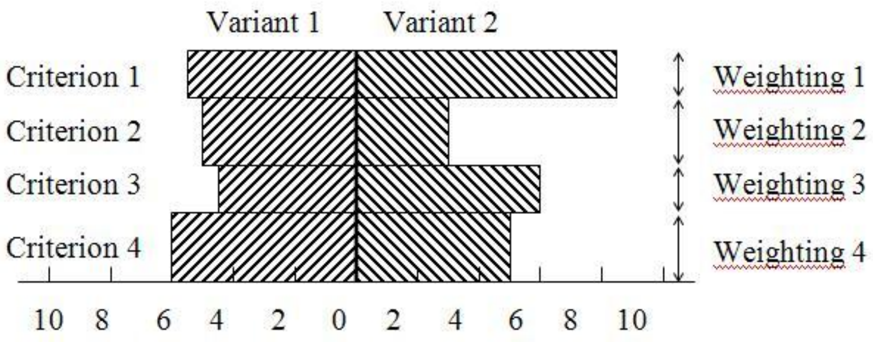


Figure 2.12. *An example of two value profiles (Figure created based on: Pahl et al. 2007, p. 123). Both variants have the same summed value but variant 1 is preferable for its more balanced profile.*

As mentioned earlier, the outcome of the conceptual design phase is one or several principle solution(s). The development continues from this (these) solution(s) in the embodiment design phase.

2.4. Ulrich's and Eppinger's methodology

Ulrich's and Eppinger's methodology presents methods, whose aim is to improve co-operation between marketing, design and manufacturing functions. Methods concentrate on developing engineered and physical products. (Ulrich & Eppinger 2008, p. 2) Therefore the methodology can easily be applied to the development task of this thesis.

The methodology consists of six phases: 0) planning, 1) concept development, 2) system-level design, 3) detail design, 4) testing and refinement and 5) production ramp-up (Ulrich & Eppinger 2008, p. 14).

This thesis covers only the concept level and therefore only phases 0 and 1 are presented.

2.4.1. Phase 0: Planning

The planning phase includes defining a customer segment, goals, restrictions and presumptions of a product. Planning begins by identifying possible targets for development. The best project is selected by assessing and prioritizing the detected opportunities on the grounds of company's competitive strategy, technological trajectories, market segmentation and product platforms. After the most promising development opportunity has been selected, resources and timing of the project must be determined. The pre-planned project must then be summarized in a product vision that describes the main goal on a general level. The final outcome of the phase 0 is a mission statement. The mission statement includes the most important information about the decisions concerning the project made by this stage. (Ulrich & Eppinger 2008)

Typical data included in the mission statement are: (Ulrich & Eppinger 2008, pp. 47-48)

- product description
- benefit proposition
- key business goals
- target market(s)
- assumptions and constraints
- stakeholders

To ensure that the right project has been chosen, it is worthwhile to reflect on the results and the process at the end of the planning phase. This is done by asking questions concerning the project. The mistakes detected at this point are easier and cheaper to correct than later during the development process. (Ulrich & Eppinger 2008, pp. 49-50)

2.4.2. Phase 1: Concept Development

In the concept development phase the goal is to identify customer needs, create several concepts and select the best concept(s) after a careful evaluation. An input of concept development is the output of the planning phase: the mission statement. Concept development consists of seven steps. The steps are 1.1) identifying customer needs, 1.2) establishing target specifications, 1.3) generating product concepts, 1.4) selecting product concept(s), 1.5) testing product concept(s), 1.6) setting final specifications and 1.7) planning downstream development. Economic factors, prototyping and benchmarking must be managed over the whole concept development phase. Proceeding within the phase is rarely completely linear. Designers must often return to the previous steps. (Ulrich and Eppinger 2008)

Step 1.1. Identifying customer needs

The goal of the first step (1.1), the identification of customer needs, is to make sure that every essential customer need is observed and latent needs are also detected. It is also important that people who work at the project understand these needs. The first task in the identification of customer needs is to gather information by interviewing customers, arranging focus group meetings or observing the use of the product. Gathered information must then be changed to customer needs. (Ulrich & Eppinger 2008) Basic rules for forming needs are: (Ulrich & Eppinger 2008, pp. 62-63)

- describe what the need is – not how it could be solved
- be specified
- select positive formulation instead of negative one
- use the product as a subject – not as an object
- keep the need neutral: express needs without words “must” and “should”

Once the needs have been formed, they must be divided to primary and secondary needs. After that their importance is rated relatively. Like in the planning phase, the identification of customer needs also ends in asking questions about the results and the process. (Ulrich & Eppinger 2008)

The customer needs don't, however, offer project members information that would be explicit enough for the development process. For that reason the customer needs are translated into product specifications. Specifications include both a metric and a value. Product specifications define detailed properties that the product should have. (Ulrich & Eppinger 2008)

Step 1.2. Establishing target specifications

After the customer needs have been defined, the target specifications are adjusted (step 1.2). Because of the iterative nature of product development, the target specifications often change dynamically over the development process. Therefore the final specifications are established not until the concept has been tested (step 1.6). (Ulrich & Eppinger 2008)

At the beginning of the target specifications adjusting, a list of metrics is created (Ulrich & Eppinger 2008, p. 75). An example of the list of metrics is shown in Table 2.8.

Table 2.8. *An example of a list of metrics (Table created based on: Ulrich & Eppinger 2008, p. 76).*

Metric number	Need numbers	Metric	Importance	Units
1				
2				

After the list of metrics has been created, the values for the metrics from competitive products are gathered and inserted into the list. An example of a list of metrics with benchmarking information is presented in Table 2.9. (Ulrich & Eppinger 2008, p. 79)

Table 2.9. *An example of a list of metrics with benchmarking information (Table created based on: Ulrich & Eppinger 2008, pp. 80-81).*

Metric number	Need number(s)	Metric	Importance	Units	Competitor A	Competitor B
1						
2						

The next task is to establish marginal and ideal values for the metrics of the product. Marginal values are such that by fulfilling them the product will still be acceptable, whereas ideal values are the ones to be aspired. Like in earlier steps, the results must be checked before moving to the next step. (Ulrich & Eppinger 2008) An example of target specifications can be seen in Table 2.10. in the next page.

Table 2.10. *An example of target specifications (Table created based on: Ulrich & Eppinger 2008, p. 84).*

Metric number	Need number(s)	Metric	Importance	Units	Marginal value	Ideal value
1						
2						

Step 1.3. Generating product concepts

The next step in the concept development phase is to generate product concepts (step 1.3). Ulrich and Eppinger define that "A product concept is an approximate description of the technology, working principles, and form of the product" (Ulrich & Eppinger 2008, p. 98). Ulrich and Eppinger present a method of five steps to generate concepts. Concept generation begins with clarifying the problem by formulating the main problem and, when needed, decomposing the problem into smaller pieces (step 1). One way to complete the decomposition is to create a function diagram, illustrated in Figures 2.13. and 2.14. A single box includes the main function, which is then divided to several subfunctions. (Ulrich & Eppinger 2008)

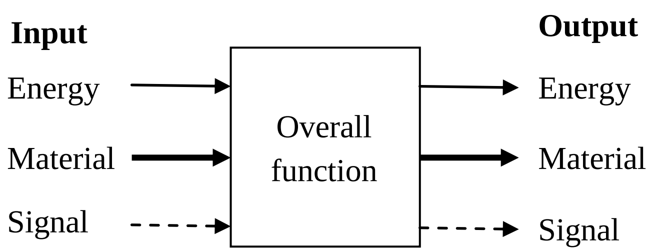


Figure 2.13. *An overall function with energy, material and signal flows (Figure created based on: Ulrich & Eppinger 2008, p. 102).*

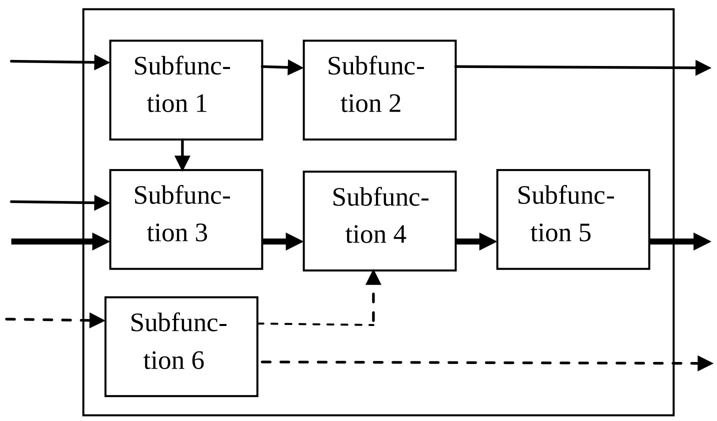


Figure 2.14. *An example of a subfunction diagram (Figure created based on: Ulrich & Eppinger 2008, p. 102).*

In the function diagram energy, material and signal flows are marked between the subfunctions in case they are easily identified. Several diagrams are normally possible and the problem can also be broken into smaller pieces based on user actions or the most important customer needs. (Ulrich & Eppinger 2008)

The second step of generating concepts (step 1.3) is to search solutions for the main problem and the subproblems externally for instance from lead users, literature or by benchmarking. If no eligible solution is found from external sources, the solutions are searched internally (step 3). In the internal search the knowledge and creativity of project team members are utilized. Solution ideas can be searched individually or in groups. In any case, a large number of ideas should be represented without prejudices. For instance analogies, related and unrelated stimuli, wishes and the gallery method can be used to stimulate the creativity of team members. Sketching ideas or using 3D media may also be easier than representing ideas verbally or in a textual form. The judgment of created ideas should not occur immediately after they have been born but in a few days or weeks – depending on a project. (Ulrich & Eppinger 2008)

In the fourth step of generating concepts (step 1.3) the searched solutions are classified either by a concept classification tree or by a concept combination table, after which the results and the process are thought over (step 5) (Ulrich & Eppinger 2008).

Step 1.4. Selecting product concept(s)

The fourth step in the concept development phase is selecting product concept(s) (step 1.4). In this step concepts are assessed on the grounds of specified criteria, compared with each other and finally the best concept(s) is (are) chosen. Ulrich and Eppinger recommend that the best concept is selected by first screening the concepts and then scoring them. The purpose of screening the concepts is to reduce the amount of possible concepts, whereas concept scoring is applied to select one, or in some cases a few, concept(s) for further development. If the screening already reveals the best concept, scoring is not needed. (Ulrich & Eppinger 2008)

Both concept evaluation stages (screening and scoring) begin from creating a selection matrix. In the selection matrix concepts are rated according to selection criteria; in screening by plus sign, minus sign or zero and in scoring numerically. In the scoring stage criteria are also weighted. According to the rates the concepts are ranked in order of superiority. After the ranking, concepts can be improved or combined, after which newborn concepts are rated and the ranking is repeated with old and new concepts. (Ulrich & Eppinger 2008) An example of a selection matrix in concept scoring is shown in Table 2.11. in the next page. In the table, the concept BC has been combined from the concepts B and C.

Table 2.11. *An example of a selection matrix in concept scoring (Table created based on: Ulrich & Eppinger 2008, p. 134).*

		Concept A		Concept BC		Concept D	
Selection criteria	**Weight**	Rate	Weighted score	Rate	Weighted score	Rate	Weighted score
Criterion a							
Criterion b							
Total score	∑ = 100 %		∑ =		∑ =		∑ =
Rate							

Once the rating is completed, the best concept(s) is (are) chosen for further development. Especially in the scoring stage the decision can be difficult, as the highest ranked concept(s) may not necessarily become automatically selected. The right selection is often ensured by executing a sensitivity analysis for the step of selecting product concept(s). Like all the previous steps, the whole step must be reflected on, once the final decision about the concept has been made. (Ulrich & Eppinger 2008)

Step 1.5. Testing product concept(s)

The step after the concept selection is testing product concept(s) (step 1.5). In this step comments and opinions about the concept description are gathered from a chosen customer group. Concept testing can also be applied when the decision about which concept to choose is to be made. The goal is defined in the beginning of the testing, after which the customer group and the format of the survey are selected. The next task is to explain the concept(s) to the members of the customer group, after which the results are measured and interpreted. At the end of the step, the results are checked. (Ulrich & Eppinger 2008)

Step 1.6. Setting final specifications

In step 1.6 the final specifications are set. The requirements of the product may have been changed during the concept development phase and therefore the target specifications must be updated. The challenge of this step is in making trade-offs. According to Ulrich and Eppinger establishing the final specifications consists of five steps. First, analytical and physical technical models are developed. Second, a cost model is created. On the grounds of the information from the technical and cost models, specifications are revised and needed trade-offs are made. In case of a complicated product, specifications are furthermore flowed down to subsystems. The step 1.6 ends in checking the results. (Ulrich & Eppinger 2008) Table 2.12. in the next page offers an example of the final specifications.

Table 2.12. *An example of the final specifications (Table created based on: Ulrich & Eppinger 2008, pp. 84 & 90).*

Number	Metric	Unit	Value
1			
2			

1.7. Planning downstream development

The final step of the concept development phase is planning downstream development (step 1.7). In this step timing and resources for the rest of the project are determined. According to Ulrich and Eppinger the design structure matrix (DSM), Gantt Charts and PERT charts are suitable tools for planning timing and resources. (Ulrich & Eppinger 2008)

2.5. Combined methodology to be used

The main features of the first two phases of Pahl et al.'s and Ulrich's & Eppinger's methodologies are fairly similar. The basic idea is equal but the methods described in the books *Engineering Design: A Systematic Approach* and *Product Design and Development* differ slightly. This section defines a methodology that combines the two earlier presented methodologies to obtain the best possible background for this thesis. Figure 2.15. illustrates the combined methodology. The phases are introduced in the following subchapters.

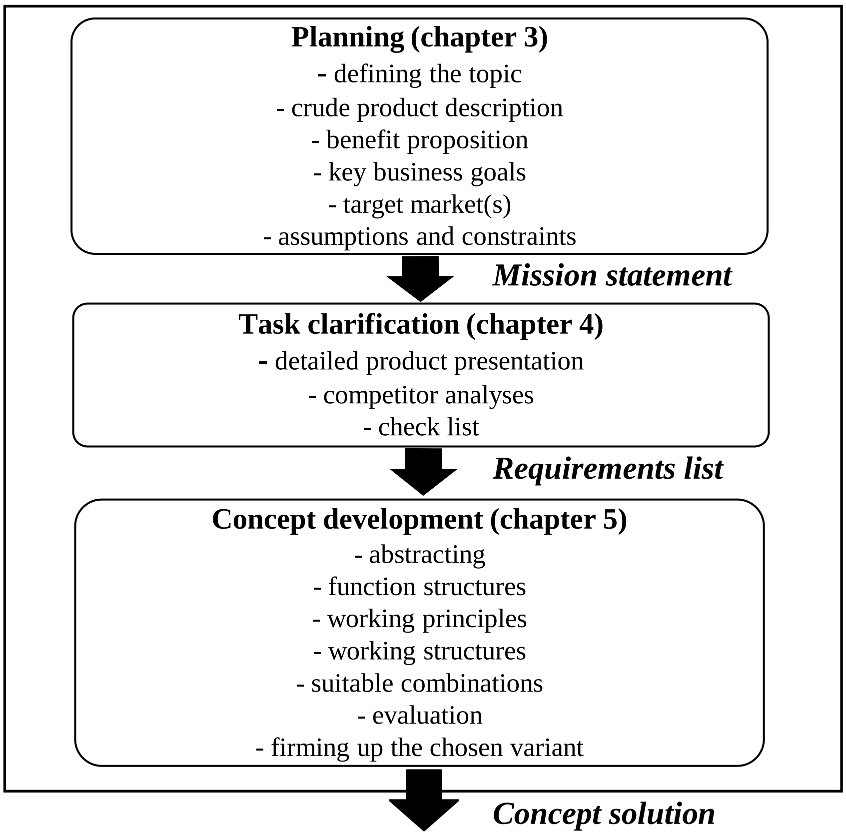


Figure 2.15. *The combined methodology to be used in this thesis.*

2.5.1. Planning

Both theories begin with defining the target of development. Customer needs had already been identified before starting this project and therefore no customer inquiry will be executed. This thesis exploits the planning phase from Ulrich and Eppinger by creating a mission statement. According to section 2.4.1. a mission statement usually includes the following information: (Ulrich & Eppinger 2008, pp. 47-48)

- product description
- benefit proposition
- key business goals
- target market(s)
- assumptions and constraints
- stakeholders.

The topics above, despite of stakeholders, are discussed in Chapter 3.

2.5.2. Task clarification

Task clarification in the combined methodology will begin with a detailed presentation of the production drill rigs in question. Ulrich's and Eppinger's list of metrics without need numbers and importance (see Table 2.8.) is created based on the information from the mission statement and the product presentations.

A competitor analyses will be executed next. The data from the competitor analyses will be added to the list of metrics with the same wishes and demands as in the list of metrics filled with product presentation information.

The check list presented by Pahl et al. (2007, p. 149) will be looked through before the final requirements list will be created. The check list is illustrated in Appendix 4. Specifications found with the help of the check list are added to the list of metrics.

Finally, when all the possible specifications are defined, they are gathered logically to a requirements list described by Pahl et al. (see table 2.5). Rating of the wishes is left outside of this thesis.

Task clarification is covered in Chapter 4.

2.5.3. Concept development

Conceptual design is defined in detail in Pahl et al.'s methodology. Thus, this thesis mainly follows Pahl et al.'s methods. The steps from 2.1 to 2.5 are performed as described in section 2.3.2. In contrast with the order of steps in Pahl et al.'s book, evaluating variants (step 2.7) will be executed before firming up into principle solution variants (step 2.6) in this thesis. In practice this means that the estimated calculations, crude sketches etc. are created only for the chosen variant(s).

In step 2.3. (Searching for working principles) ideas are generated in a Tuplatiimi [double team] meeting. Tuplatiimi is a solution finding method that is created and owned by Innotiimi Oy (Innotiimi Oy). A problem is presented at the beginning of a Tuplatiimi meeting, after which an actual idea creation is started. The method consists of three phases. First, the solution ideas are generated alone. Second, the best ideas are selected in groups of two, introduced to other groups and fastened on the wall. Third, the ideas on the wall are arranged and rated by giving votes. (Wikipedia)

In addition, Pahl et al. suggest that a selection chart or a compatibility matrix for the solutions of the subfunctions is created after the working structures are formed (see section 2.3.2). In this thesis the subfunctions are anyhow evaluated already before forming the working structures by modifying the morphological matrix. Several combinations from the solutions are formed and the best suitable working structures are then chosen by creating a selection chart for the combinations.

In the evaluation step the criteria are defined and weighted in a horizontal objective tree according to Cost-Benefit Analysis (see section 2.3.2). The sum of the weightings is 1. Instead, in valuing the criteria the VDI 2225 method is used, because the estimations of the values are not accurate under most of the criteria. In the comparison action the strict percentual limits are not exploited but the best three to five solutions will be moved to uncertainty inspection and profiling. Iteration will be performed if needed.

The concept development ends with one concept solution that describes the functionality, shape and dimensions of the product. Functionality will be illustrated by simulating the movements of the boom module, whereas the shape and dimensions are shown as figures from a 3D-model. Tentative strength and stability inspection are executed according to the 3D-model.

Concept development is performed in Chapter 5.

2.6. Perttula: Verification and validation

In this thesis it is highly important to ascertain that the research proceeds to the right direction. The progress must be investigated several times during the development process. Controlling the direction of the process can be executed by verification and validation. The terms verification and validation are introduced next.

According to Perttula (2007, p. 14) verification denotes ensuring that the developed product, component or sub-assembly fulfills the requirements of the specifications. Validation, in turn, aims at assuring that the customer needs are gratified (Perttula 2007, p. 15). In other words, verification is an act to ensure whether things have been made right, whereas validation concentrates on a question of whether the right things have been made. Perttula (2007) calls verification and validation shortly V&V in his doctoral thesis. This abbreviation is used in this thesis from now on.

V&V helps product design engineers for instance in the following tasks: (Perttula 2007, p. 16)

- determining errors
- integrating system level
- estimating reliability
- estimating performance
- checking that the product is lawful and fulfills the regulations

According to Andersson & Runeson (2002) and Stevens et al. (2000) (as cited in Perttula, 2007, p. 20 Figure, 20) methods used in V&V can be divided into four categories: testing, analysis, comparison and assessment.

Testing is divided into three areas that are functional, environmental and reliability tests (Perttula 2007, p. 20, Figure 9). Perttula defines these three areas of testing the following way; “Functional tests make sure that the design meets the interface, compatibility and performance requirements”; “The purpose of environmental testing is to ensure that the design works in real conditions” and “Reliability testing estimates the lifetime and the field failure rate (FFT) of the design” (Perttula 2007, pp. 20-21).

Another method to complete verification is to accomplish an analysis. In an analysis the product is tested by means of mathematical models, simulations and documentation. Accomplishing verification without physical models is usually remarkably more economical than building a prototype. (Perttula 2007, p. 22)

Perttula (2007, p. 22) defines comparison as a way to perform verification to be exploitable “… when a product, sub-system or component has been verified earlier and can be re-used in a new system”.

Like accomplishing an analysis, performing an assessment needs no physical model to be completed (Perttula 2007, pp. 22-23). According to Perttula (2007, p. 22) “Verification by assessment includes inspection, demonstration and review”. The aim of inspection is to identify defects from static documents before testing activities (Gilb & Graham 1993, see Perttula 2007, p. 23; Perttula 2007, p. 23). In demonstration, on the other hand, customer’s opinion of the functionality of the product is canvassed (Perttula 2007, p. 24), whereas review can be considered “… as a formal examination of a document or product for comment and approval” (Mooz et al. 2003, see Perttula 2007, p. 24).

2.6.1. Implication of V&V for this thesis

Verification and validation is exploited in many ways in this thesis. Testing will not be executed within the thesis as the goal of this project is to create a technically convincing concept. For that reason the process does not reach the prototyping level and a lack of physical objects inhibits the use of testing methods.

Analysis, instead, will be exploited in this thesis by means of 3D modeling and simulation. A crude version of the front frame will be modeled and the movements of the joints will be analyzed by simulation.

Comparison between current models and the created new front frame is accomplished particularly for dimensions.

Also assessment will also be exploited in this thesis – especially reviewing will be executed several times over the development process; first after the planning, then after the task clarification and also during the concept development.

2.7. Strength calculations

When designing a new part, it is important to make sure the part sustains the strains that are directed at it. In this thesis bending and torsional stresses are investigated at a rough level (Outinen & Salmi 2004, pp. 463-464). This means that several simplifications are made to the structures. The aim is to get suggestive dimensions for the structures. The exact calculations are left outside of this thesis but they must be executed before starting any production.

2.7.1. Bending stress

Calculating bending stress begins with solving the section modulus (Outinen & Salmi 2004, p. 463). The profile shape of the current beam in the front frame is a hollow rectangle. The section modulus of that profile is: (Valtanen 2012, p. 216)

$$W_z = \frac{BH^3 - bh^3}{6H}, \qquad [1]$$

where B is outer width, b inner width, H outer height and h inner height (see Figure 2.16.).

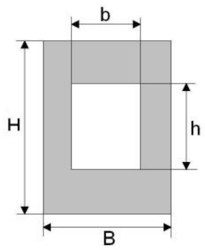


Figure 2.16. *Dimensions of the section modulus of a hollow rectangle (Figure reproduced from: Valtanen 2012, p. 416).*

The next step is to solve the bending moments of the structure (Outinen & Salmi 2004, p. 463). The situation of the front frame can be simplified as in Figure 2.17. in the next page.

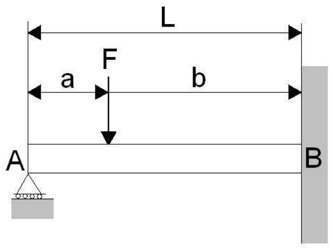


Figure 2.17. *Dimensions in the bending situation of the current front frame (Figure reproduced from: Valtanen 2012, p. 422).*

The biggest bending moment occurs either at place B or under the force. The bending moments are counted by the following equations: (Valtanen 2012, p. 422)

$$M_B = -\frac{Fab}{L}\left(1 - \frac{b}{2L}\right) \qquad [2]$$

$$M_F = -\frac{Fab^2}{L^2}\left(1 + \frac{a}{2L}\right) \qquad [3]$$

The bending stress can now be solved by the following equation: (Valtanen 2012, p. 471)

$$\sigma_t = \frac{M}{W}, \qquad [4]$$

where M is the maximum of M_B and M_F, and W is W_Z.

2.7.2. Torsional stress

Like with bending stress, torsion stress calculations begin with solving the maximum torsion moment (Outinen & Salmi 2004, p. 464). The equation of moment is

$$M = F \cdot r, \qquad [5]$$

where r is the perpendicular distance of the force from the moment point (Valtanen 2012, p. 219).

The section modulus in torsion of a hollow rectangle is

$$W_v = 2bht_{min}, \qquad [6]$$

where b is the width, h the height and t_{min} the minimum thickness of the plate accordant to Figure 2.18. in the next page (Valtanen 2012, p. 452).

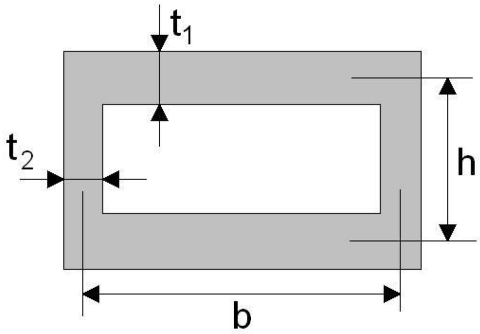


Figure 2.18. *Dimensions of the section modulus in torsion of a hollow rectangle (Figure reproduced from: Valtanen 2012, p. 452).*

Now that both the torsion moment and the section modulus in torsion are solved, the torsional stress can be calculated by the following equation: (Valtanen 2012, p. 479)

$$\tau_1 = \frac{M_v}{W_v}, \quad [7]$$

where M_v=M.

3. PLANNING

This section defines the topic and the preliminary knowledge of the development process of this thesis. The preliminary knowledge will be gathered to a mission statement.

3.1. Defining the topic of the thesis

A proposal for developing production drill rigs came from a design engineer of the company. Several alternatives to approach the task emerged from customers' feedbacks. According to the customer needs, possible subject proposals were:

- combining DL411 (classic model) and DL421 (frame model) into one model
    - improving safety
    - rationalizing the offering
    - allowing inclined fans with DL421 as well (now they are possible only with DL411)
- developing DL421
    - easing the change and maintenance of hosing
    - improving drilling stability
    - easing the drilling of underhand holes
    - averting the front frame to hit the ground when tramming in a ramp *
    - redesigning the shape and the dimensions of the front frame

* tramming: driving

The subject proposals are discussed and the decision is made based on the opinion of the product line manager. The chosen subject is to investigate, whether combining the two models into one model by adding a feature that enables the inclined fans in DL421 is possible. Hosing and stabilizing the DL421 are also targets for improvement of the new front frame.

3.2. Preliminary knowledge

The target of this development process is production drill rigs (long-hole drilling rigs). Production drill rigs drill long holes into the ore. A simplified structure of a rig includes a cabin/canopy module, front end module, rear end module, boom module, drilling module and finishing module. The simplified structures of DL411 and DL421 are presented in Figures 3.1. and 3.2. in the next page. The front frame belongs to the boom module. Production drill rigs are introduced in more detail in Chapter 4: Task clarification.

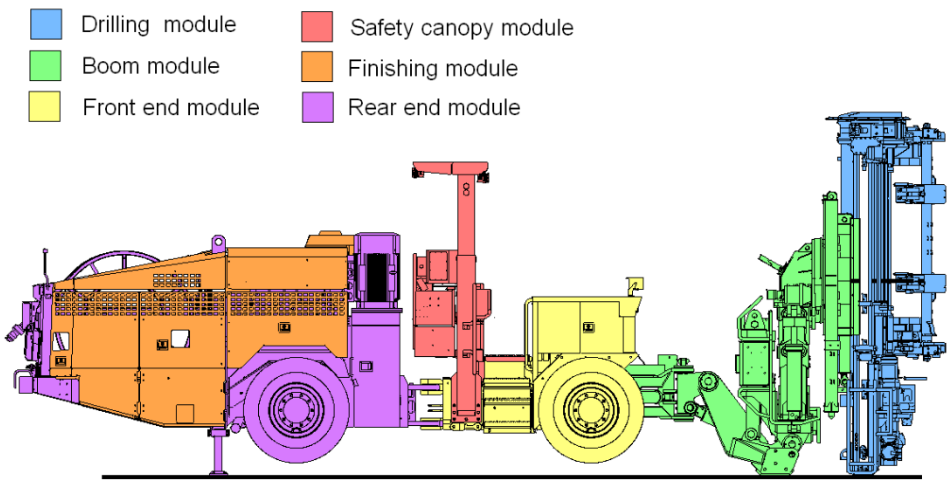


Figure 3.1. *A simplified structure of DL411 (Figure modified from: Windchill).*

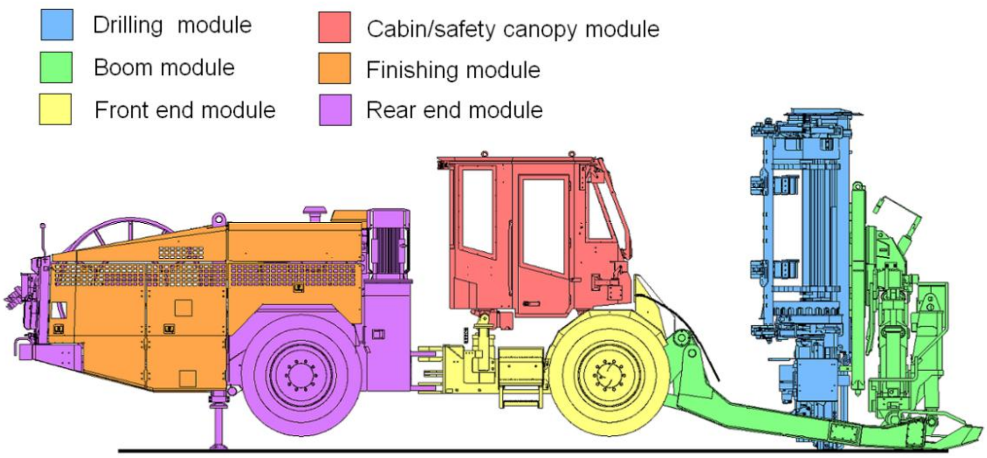


Figure 3.2. *A simplified structure of DL421-C (figure modified from: Windchill).*

Standardizing the front frame would rationalize the supply, which would reduce designing work as well as ease production and assembly in the future. A new solution would also increase safety of an operator. In addition, the sale of DL411 is probably going to be proscribed in the whole world due to safety reasons in the future. Anticipation of standard and directive changes enables an up-to-date supply for customers.

The main business goal of this project is to achieve economic savings by rationalizing the supply. Another important goal is to keep customers satisfied by easing the maintenance and improving the stability of DL421.

The target market of the new product is the global mining industry; especially the current customer segments of both existent models. It is important to cater for the customers who use the model that might be forbidden worldwide in the future.

At the beginning of the project, some assumptions have been made. The first assumption is that safety regulations are going to be changed in developing countries as well. Another assumption is that there will be no significant breakthrough in the area of long-hole drilling in the near future. A new revolutionary drilling technology would make the development of current products worthless.

Besides making assumptions, some constraints are set at this point. The costs of the product should not rise from the present-day's price. In addition, dimensions of the rigs should not grow significantly.

The preliminary knowledge is gathered to the mission statement in Table 3.1.

Table 3.1. *Mission statement of the development project.*

Crude product presentation	• a front frame for production drill rigs
Benefit propositions	• rationalizes the supply • increases safety • ensures supply that is in accordance with standards and directives
Key business goals	• economic savings by rationalizing the supply • customer satisfaction
Target market	• mining industry • markets of existent models
Assumptions	• a global tightening of standards and directives • no significant breakthrough in drilling
Constraints	• costs should not rise • dimension should not grow significantly

At this stage validation is needed. The mission statement is approved by Juha Piipponen.

4. TASK CLARIFICATION

4.1. Product presentations

In this subsection the production drill rigs (long-hole drilling rigs) DL411 and DL421 are introduced. The models belong to the same size class but differ from the front part. The code DL in the names of the rigs comes from words drilling longhole. The first number of the name indicates the envelope size, the second the type of the drilling boom and the third the revision of the model. The envelope size tells the size of the tunnel the rig can tram in. Tramming is used as a synonym for driving in mining terminology. Number one in the drilling boom type means the classic type and number two the frame type. Drilling boom types can be seen in Figure 4.1. The revision number (starting from 0) tells the version of the model. (Sandvik Mining and Construction) The models are first presented separately and then compared with each other.

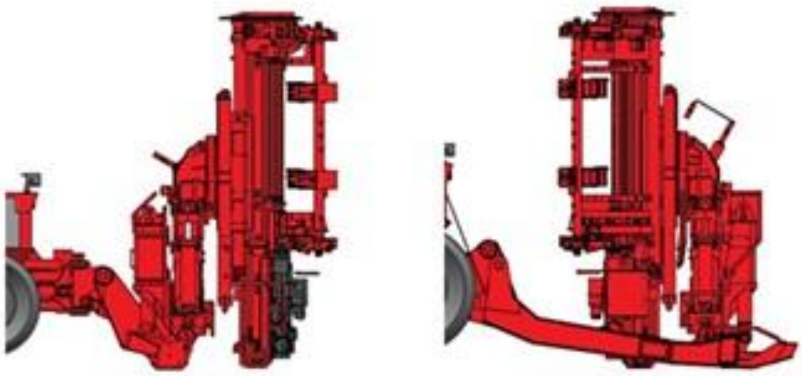


Figure 4.1. *Classis type front frame (left) and frame type front frame (right) (Figure modified from: Technical Specification, DL411-15; Technical Specification, DL421-15)*

As mentioned earlier, this thesis deals with models DL411 (the classic version) and DL421 (the frame version). Both rigs are available with different sized powerpacks. The rigs with 90-kW powerpacks have been selected for the comparison executed in this chapter. 90-kW powerpacks are indicated by adding number 15 behind the name of the rigs. DL421 is available both as a cabin and as a safety canopy version, whereas DL411 does not have a canopy opportunity. The capital letter C at the end of the name indicates cabin. For example DL421 with a 90-kW powerpack and a cabin is named DL421-15C.

DL411 and DL421 with same sized powerpacks are mostly composed of the same components. (Technical Specification, DL411-15; Technical Specification, DL421-15;

Technical Specification, DL421-15C) Examples of common components in DL411-15, DL421-15 and DL421-15C are: (Technical Specification, DL411-15; Technical Specification, DL421-15; Technical Specification, DL421-15C)

- drilling module options
- rock drill
- boom
- control system type
- main switch
- water pump
- air cleaner
- axles
- tires
- diesel engine and
- rear hydraulic jack

4.1.1. DL411

The drilling boom type of DL411 is classic (see Figure 4.1. in page 34). In the drilling position the front frame touches the ground relatively close to the carrier frame. The canopy of the model is small and there is no option for cabin.

While drilling, the operator must see the drilling module from the front. This means that he or she must stand in front of the rig or drill with the help of cameras. Figure 4.2. shows the structure of the canopy, the front frame and the drilling module. The place of the operator during the drilling can also be seen in that picture. Some dimensions vary depending on a feed of the drilling module. All the dimensions given in this thesis are from the rigs with LF1606 drilling module. (Technical Specification, DL411-15)

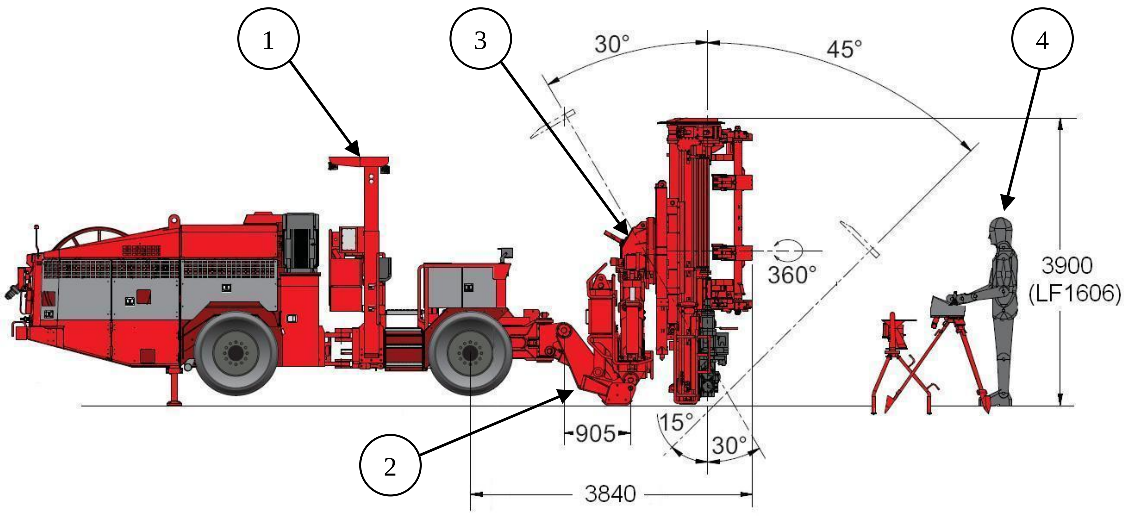


Figure 4.2. *A side view of DL411 while drilling. Number 1 points to the canopy, 2 to the front frame, 3 to the boom and 4 to the operator. (Figure modified from: Technical Specification, DL411-15)*

With DL411 the operator can drill plane rings and fans. Both vertical and inclined plane rings are possible. The front frame stabilizer turns 35° both to the left and to the right and this feature enables drilling inclined fans as well (see Figure 4.3.). (Technical Specification, DL411-15) The turning angles, some drilling dimensions, vertical fan and inclined fan are visible in Figure 4.3. In Figure 4.3. dimensions 1,030 and 650 indicate the minimum distance between a wall and a vertical hole in millimeters.

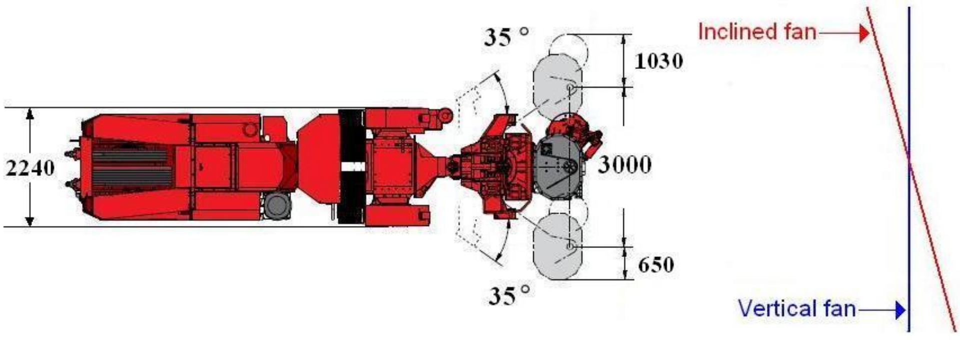


Figure 4.3. *A top view of DL411 while drilling. The turning angle of the front frame is ± 35° and the parallel coverage is 3 meters. The difference between the vertical and the inclined fan is also marked to the picture. (Figure modified from: Technical Specification, DL411-15)*

In DL411 the drilling module is on the front carrier frame during tramming, like shown in Figure 4.4. The angle between the ground and the boom is 17° and between the ground and the rear end of the rig 15°. (Technical Specification, DL411-15) The bigger the angle the easier the rig is to tram in ramps. The position of the boom module during tramming and the angles can be seen in Figure 4.4.

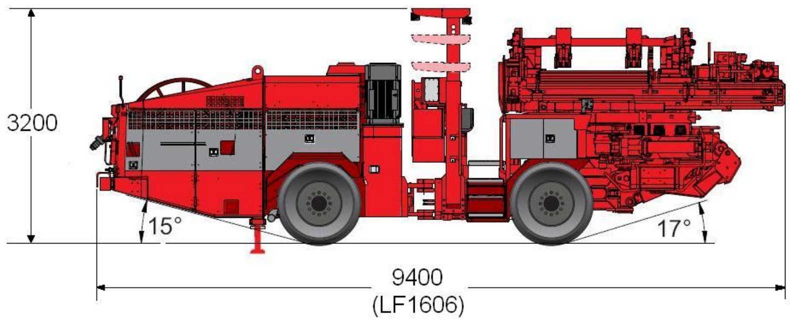


Figure 4.4. *A side view of DL411 while tramming (Technical Specification, DL411-15).*

The front frame of DL411 is shown from the side, front and above in Figure 4.5. in the next page. The weight of the front frame is 1,750 kg (Unigraphics NX).

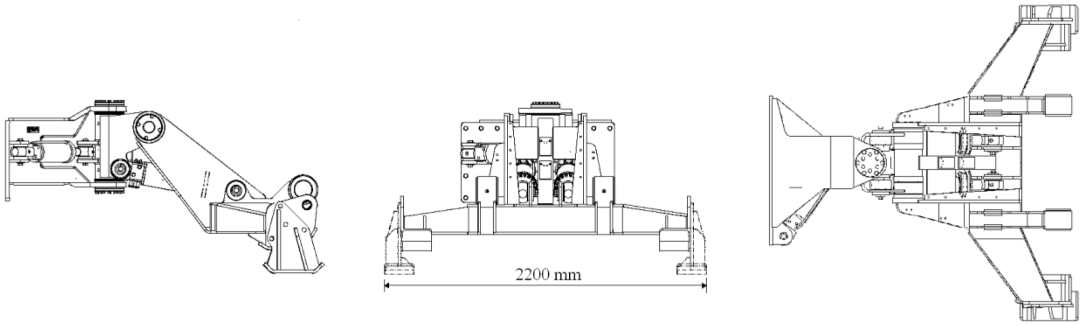


Figure 4.5 *The front frame of DL411 from the side (left), front (in the middle) and above (right) (Figure modified from: Windchill).*

4.1.2. DL421

The drilling boom type of 421 is frame. The front frame divides to two beams right after the boom support and these two beams reunite at the front end of the rig (see Figure 4.7.). Thus the beams form a closed frame, from which the drilling boom type gets its name. The front frame touches the ground further off the carrier frame than the classic-type front frame. (Technical Specification, DL411-15; Technical Specification, DL421-15)

Compared with the safety canopy version, the cabin version of DL421 is safer for the operator but at the same time more expensive and may need more maintenance because of higher equipment level. Unlike in DL411, in DL421 the operator stays under the canopy or inside the cabin during drilling. The structures of the front frame and the cabin during the drilling are shown in Figure 4.6.

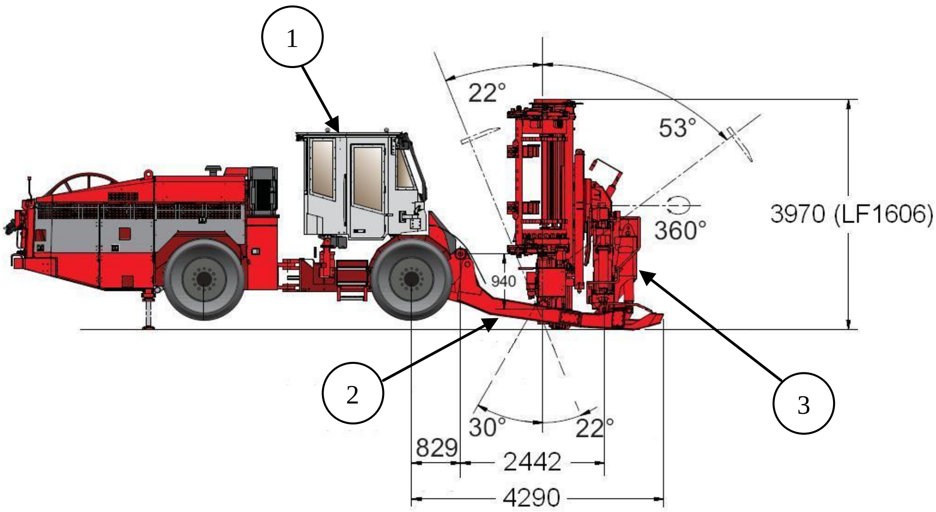


Figure 4.6. *A side view of DL421-15C while drilling. Number 1 points to the cabin, 2 to the front frame and 3 to the boom. (Figure modified from: Technical Specification, DL421-15C; Windchill)*

Like DL411, DL421 is capable of drilling plane rings and fans. Inclined plane rings are also possible. Unlike DL421, the frame type front frame does not turn, which makes drilling inclined fans impossible. Figure 4.7. illustrates the parallel coverage of the drill, the minimum distance between the wall and the vertical hole and the distance from the drill to the top of the frame.

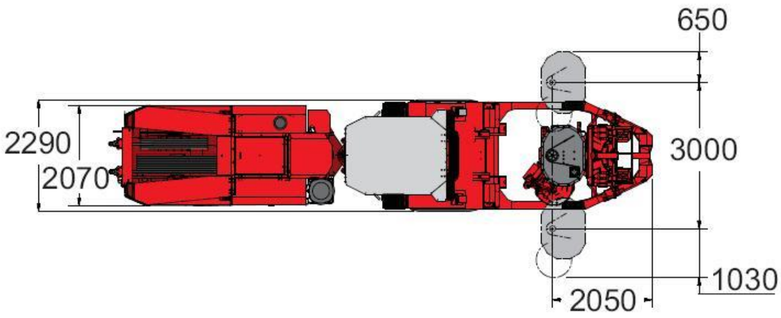


Figure 4.7. *A top view of DL421-15C while drilling (Figure modified from: Technical Specification, DL421-15C)*

While tramming, the drilling module is either standing or lying crosswise in respect to the carrier (see Figure 4.8.). Tramming width and height vary according to the feet of the drilling module. When the drill is crosswise, the rig is approximately 1 – 1.6 meters wider than when the drill is standing. Depending on the feed and whether the rig has the canopy or the cabin, the position of the drilling module affects the tramming height from 0 to 0.55 meters. (Technical Specification, DL421-15; Technical Specification, DL421-15C)

The angle between the front frame and the ground is 11° and between the rear carrier frame and the ground 16°. These angles affect tramming in ramps. Figure 4.8. shows both the standing and the lying position of the boom module in a cabin version of DL421.

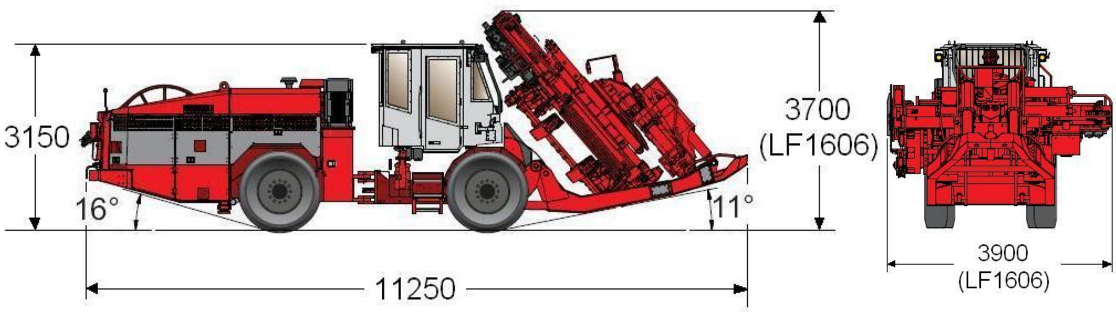


Figure 4.8. *Possible positions of the boom module of DL421 (cabin version) while tramming. Left the standing and right the lying position. (Figure modified from: Technical Specification, DL421-15C)*

The front frame of DL421 is shown from the side, front and above in figure 4.9. in the next page. The weight of the front frame is approximately 2,100 kg (Unigraphics NX).

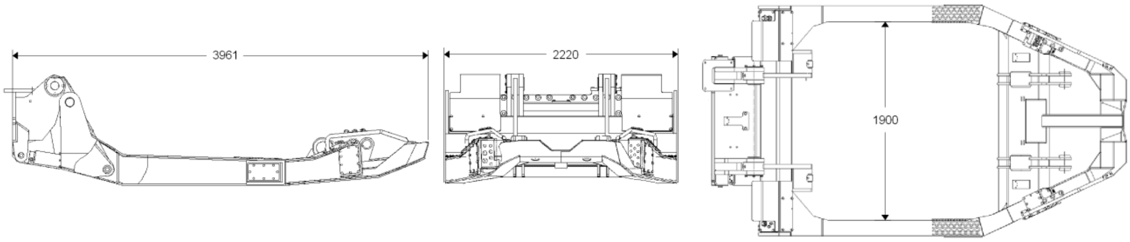


Figure 4.9. *The front frame of DL411 from the side (left), front (in the middle) and above (right) (Figure modified from source: Windchill).*

4.1.3. The comparison of DL411 and DL421

As mentioned earlier, DL411 and DL421 have many common components (see the list of the examples of the common components in page 35). However, the differences at the front ends of the rigs cause some divergence in physical dimensions and drilling characteristics. Some parameters have been gathered to Table 4.1. in the next page. Numbers in that table are from the rigs with 90-kW powerpacks. Figure 4.10. illustrates the turning angles of the models and Figure 4.11. coverage area dimensions.

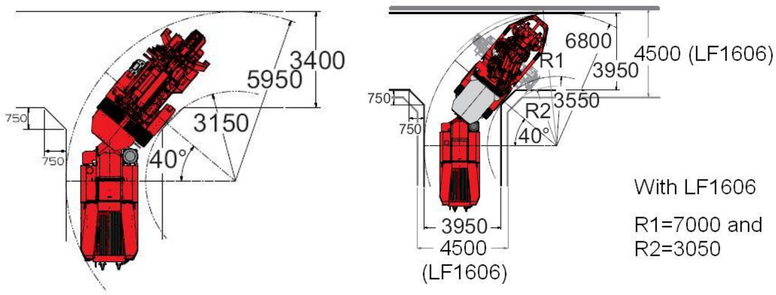


Figure 4.10. *The turning angles. Left DL411-15, right DL421-15C. Grey lines and radiuses R1 and R2 in the right side rig illustrate the situation, when the drilling module is crosswise. (Figure modifies from: Technical Specification, DL411-15; Technical Specification, DL421-15C)*

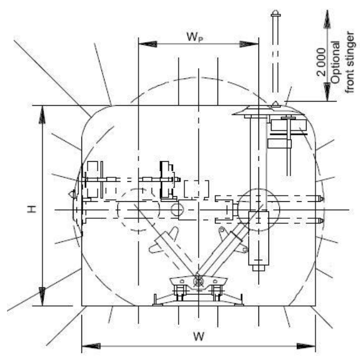


Figure 4.11. *The coverage area.* W_p *means parallel coverage, W width, and H height. The height is measured with rear stinger and the extra height received with optional front stinger is marked at the right top corner. (Technical Specification, DL411-15)*

Table 4.1. *Parameters of DL411-15, DL421-15 and DL421-15C with LF1606 drilling module (Technical Specification, DL411-15; Technical Specification, DL421-15; Technical Specification, DL421-15C; Unigraphics NX; Weights and dimensions, DL411; Weights and dimensions, DL421).*

Parameter [unit]	**DL411-15**	**DL421-15**	**DL421-15C**
Tramming length (a) [mm]	9,400	11,250	11,250
Width [mm] (b)	2,240	2,290 3,900 (c)	2,290 3,900 (c)
Width of the front frame [mm] (d)	2,200	2,220	2,220
Height, tramming (a) /drilling (e) [mm]	3,200/3,900	3,700/3,900 3,150/3,900 (c)	3,700/3,900 3,150/3,900 (c)
Distance from the front axle to the front end of the rig [mm] (e)	3,840	4,290	4,290
Turning radius, inner/outer [mm] (f)	3,150/5,950	3,550/6,800 3,050/7,000 (c)	3,550/6,800 3,050/7,000 (c)
Articulation angle [°] (f)	± 40	± 40	± 40
Turning angle of the front frame [°] (g)	± 35	± 0	± 0
Max. gradeability [°]	15 °	15 °	15 °
Max. inclination [°]	5 °	5 °	5 °
Weight [kg]	21,000	22,000	22,000
Weight of the front frame assembly [kg]*	1,450/1,750	1,500/2,100	1,500/2,100
Hole size [mm]	89-127	89-127	89-127
Maximum length of the hole [m]	54	54	54
Max. parallel coverage [mm] (h)	3,000	3,000	3,000
Min. coverage width [mm] (h)	4,170	4,170	4,170
Max. coverage width [mm] (h)	5,400	5,400	5,400
Min. coverage height [mm] (h)	4,170	4,170	4,170
Max. coverage height, with rear stinger/optional front stinger [mm] (h)	4,670/+2,000	4,670/+2,000	4,670/+2,000
Underhand drilling angles, front/back [°] (e)	30/15	22/30	22/30
Overhand drilling angles, front/back [°] (e)	45/30	53/22	53/22

(a) see Figures 4.4. and 4.8.
(b) see Figures 4.3, 4.7. and 4.8.
(c) drilling module laying crosswise while tramming
(d) see Figures 4.5. and 4.9.
(e) see Figures 4.2. and 4.6.
(f) see Figure 4.10.
(g) see Figures 4.3. and 4.7.
(h) see Figure 4.11.
* According to Weights and dimensions DL411 and DL421/Unigraphics NX (weights from Unigraphics NX rounded to the closest 50 kg)

According to Table 4.1. the biggest differences between the dimensions of the models are in tramming length, width, height, turning radiuses, front frame's turning angle and drilling angles. Because of the differences, the rigs have features that differ. Advantages and disadvantages of the models are presented in the following sub-section.

4.1.4. Advantages and disadvantages of DL411 and DL421

The smaller outside measures and turning radiuses of DL411 make the model more agile in tramming than DL421. The turning of the front frame enables the drilling of inclined fans (see figure 4.3.) and this feature makes DL411 more versatile than DL421. Drilling underhand is also slightly easier with DL411 than with DL421.

In regard to physical and drilling characteristics, DL411 seems to have more desirable features than DL421. However, DL411 has a major safety problem. A small canopy does not protect the operator during tramming as well as a bigger canopy or particularly a cabin does. In addition, during drilling, the operator does not usually stay under the canopy but on the ground in front of the rig. This creates a vast safety risk for the operator. Drilling without an operator having a roof is forbidden in many countries by standards and directives. For that reason DL411s can't be sold for instance to the countries that belong to the European Union. Thus, the most important reason for choosing DL421 instead of DL411 is the safety of the operator.

DL411 belongs to Sandvik's supply greatly for historical reasons. Earlier, the safety of the operator was not the priority of mining companies. It is likely that some day in the future the models like DL411 will be forbidden in every country.

Safety of the operator is the most significant advantage of DL421. However, there are differences in safety among DL421s too. The cabin version is safer for the operator than the safety canopy version. The canopy version rigs are mostly imported to developing countries because canopies are cheaper and require less maintenance than cabins.

Although DL421 is safer than DL411, it is, however, slightly instable in the drilling position. Especially on a grainy ground the rig can start to swing, when the drilling module is moved. This creates a risk of stumbling.

Hosing is somewhat problematic in the frame model as well. In front of the rig the hoses are located inside the beams of the front frame; safe from outward impacts. The hoses are nevertheless laborious to maintain and change. Occasionally clients relocate the hoses outside the beams and leave them unprotected to ease the maintenance.

Table 4.2. in the next page summarizes the advantages and disadvantages of DL411 and DL421.

Table 4.2. *Advantages and disadvantages of DL411 and DL421.*

Model	Advantages	Disadvantages
DL411	• Size • Agility • Ability to drill inclined fans • Underhand drilling	• Poor safety of the operator • The usage forbidden in many countries • "A leftover" from history
DL421	• Safety of the operator	• Inability to drill inclined fans • Instability in the drilling position • Hosing

Table 4.3. below lists the most important parameters, demands and wishes.

Table 4.3. *The list of specifications according to the product presentation. W indicates a wish and D a demand.*

Metric number	Metric/demand/wish	Unit/ W/D	DL411	DL421
1	Tramming length	mm	9,400	11,250
2	Width	mm	2,240	2,290
3	Width of the front frame	mm	2,200	2,220
4	Max. height, tramming/drilling	mm	3,200/3,900	3,700/3,900
5	Distance from the front axle to the front end of the rig	mm	3,530	3,961
6	Turning radius, inner/outer	mm	3,150/5,950	3,550/6,800
7	Articulation angle	°	± 40	± 40
8	Turning angle of the front frame	°	± 35	± 0
9	Max. gradeability	°	15	15
10	Max. inclination	°	5	5
11	Weight of the front frame	kg	1,450	~2,100
12	Hole size	mm	89-127	89-127
13	Max. hole length	m	54	54
14	Max. parallel coverage	mm	3,000	3,000
15	Min. coverage width	mm	4,170	4,170
16	Min. coverage height	mm	4,170	4,170
17	Underhand drilling angles, front/back	°	30/15	22/30
18	Overhand drilling angles, front/back	°	45/30	53/22
19	Safety of an operator	D	Poor	Rather good/good
20	Fulfillment of standards and directives	D	Yes	Yes
21	Fulfillment of standards and directives in the future	W	Probably not	Probably yes
22	Easiness of maintenance	W	Neutral	Rather difficult
23	Stability	W	Rather stable	Neutral

The specification list created based on the product presentation is not, however, extensive enough. The list is next filled with benchmarking information.

4.2. Competitors

There are several companies that produce mining rigs but the only real competitor of large production drill rigs is Atlas Copco. Atlas Copco has altogether 16 different production drill rigs, from which Simba M3 C, L3 C and M4 C match with Sandvik's DL411, and Simba M6 C and L6 C with DL421. Simba M3 C, L3 C and M4 C have a similar front frame structure, which is illustrated in Figure 4.12. The structure of the front frame of Simba M6 C and L6 C is presented in Figure 4.13. (Atlas Copco, products)

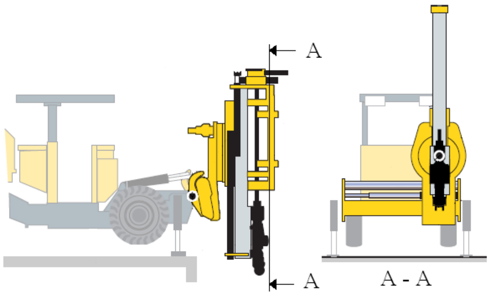


Figure 4.12. *The structure of the front frame of Simba M3 C, L3 C and M4 C. Figure presents Simba L3 C from the side (left) and a cross-section A-A (right). (Figure modified from: Atlas Copco, products)*

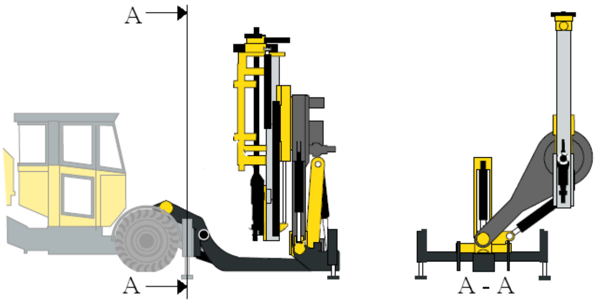


Figure 4.13. *The structure of the front frame of Simba M6 C and L6 C. Figure presents Simba M6 C from the side (left) and a cross-section A-A (right). (Figure modified from: Atlas Copco, products)*

The list of specifications is filled with benchmarking information and the results are presented in Table 4.4. in the next page. Some of the metrics are not found from the technical specifications available in the Internet and the cells of those specifications are left empty (Atlas Copco, products).

Table 4.4. *The list of specifications according to benchmarking information (Atlas Copco, products).*

Metric number	Metric/demand/wish	Unit	Simba M3 C	Simba L3 C	Simba M4 C	Simba M6 C	Simba L6 C
1	Tramming length	mm	10,500	10,500	10,500	10,500	10,500
2	Width	mm	2,350	2,350	2,350	2,210	2,210
3	Width of the front frame	mm					
4	Height, tramming (with canopy)/drilling	mm	2,875/	2,875/	2,875/	3,200/	3,200/
5	Distance from the front axle to the front end of the rig	mm	3,000	3,000	3,200	3,770	3,770
6	Turning radius, inner/outer	mm	3,800/ 6,300	3,800/ 6,300	3,800/ 6,300	3,800/ 6,750	3,800/ 6,300
7	Articulation angle	°	± 41	± 41	± 41	± 41	± 41
8	Turning angle of the front frame	°					
9	Gradeability	°	14*	14*	14*	14*	14*
10	Max. inclination	°					
11	Weight of the front frame	kg					
12	Hole size	mm	51-89 (102)	89-127	51-89 (102)	51-89 (102)	89-127
13	Max. hole length	m	51	51	51	51	51
14	Max. parallel coverage	mm	1,500	1,500	3,000	3,000	3,000
15	Min. coverage width	mm					
16	Min. coverage height	mm					
17	Underhand drilling angles, front/back	°	30/30	30/30	30/30	30/45	30/45
18	Overhand drilling angles, front/back	°	30/30	30/30	30/30	45/30	45/30
19	Safety for an operator	D	Unsafe	Unsafe	Unsafe	Rather safe/sa fe	Rather safe/sa fe
20	Fulfillment of legislation	D	Yes	Yes	Yes	Yes	Yes
21	Fulfillment of legislation in the future	W	Probab ly not	Probab ly not	Probab ly not	Probab ly yes	Probab ly yes
22	Easiness of service	W					
23	Stability	W					

* Gradeability converted from percentages to angles on equation $° = \tan^{-1}(0.01 \times \%)$ (Grader Watchman, p. 7).

4.3. Check list

The check list presented in Appendix 4 is now gone through and the new requirements discovered based on the check list are gathered to Table 4.5.

Table 4.5. *The list of specifications according to the check list.*

Metric number	Metric/demand/wish	Unit	D/W	Value
24	Position of the drill	-	D	Towards the rig
25	Extendable front frame		W	
26	Sufficient strength of the structure of the front frame		D	
27	Ability to bear resonance		D	
28	Temperature range	°C		-40…+60
29	Corrosion tolerance		D	
30	Good visibility, tramming		W	
31	Satisfactory visibility, tramming		D	
32	Good visibility, drilling		D	
33	Clear maneuverability of the front frame		W	
34	Easy to manufacture		W	
35	Long time between services		W	
36	Easy to clean		W	
37	Cheap to manufacture		W	
38	Development ready by March 30, 2012		W	
39	Development ready by April 23, 2012		D	

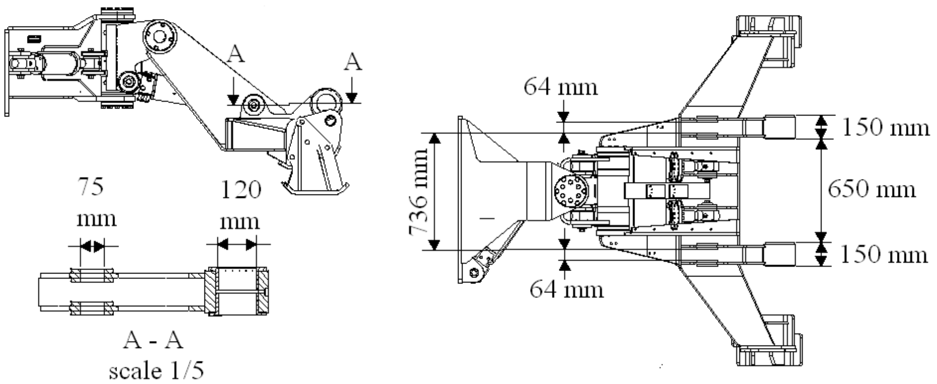


Figure 4.14. *Front frame's interface dimensions for the boom. Figure shows the dimensions of DL411 but they are the same for DL421 as well because the boom is the same. (Figure modified from: Windchill; Unigraphics NX)*

4.4. Requirements list

The requirements list can now be created based on Tables 4.3.-4.5. All the requirements are classified to wishes (W) and demands (D). It is important to note that the requirements list is a dynamic object and it must be refreshed if new information occurs during the development process. The latest requirements list is presented in the next two pages in Table 4.6. and it is the final output of the task clarification phase. An original version is shown in Appendix 5.

Table 4.6. The requirements list (1/2).

Sandvik Mining		**Requirements list for a front frame**	**Issued on: 20 April 2012 Page:1/2**
Dates of changes	Demand /Wish	Requirements	Responsible
		1. Geometry	
	D	• Tramming length ≤ 11.25 m	
	W	• Tramming length ≤ 10.5 m	
2 Jan	D	• Inner turning radius ≤ 3.55 m	
2 Jan	W	• Inner turning radius ≤ 3.2 m	
2 Jan	D	• Outer turning radius ≤ 6.8 m	
2 Jan	W	• Outer turning radius ≤ 6.0 m	
	D	• Width of the front frame ≤ 2.29 m	
2 Jan	W	• Width of the front frame ≤ 2.2 m	
	D	• Tramming height ≤ 3.7 m	
2 Jan	W	• Tramming height ≤ 3.2 m	
		2. Kinematics	
	D	• Underhand drilling angles, front/back ≥ 30/30°	Aino-Maija Mylläri
	W	• Underhand drilling angles, front/back ≥ 30/45°	
	D	• Overhand drilling angles, front/back ≥ 45/30°	
		3. Drilling area	
2 Jan	D	• Maximum parallel coverage = 3 m	
2 Jan	D	• Minimum coverage width ≤ 4.17 m	
15 Dec	D	• Minimum coverage height ≤ 4.17 m	
	W	• Ability to drill inclined fans	
		4. Forces	
20 Apr	D	• Weight of the front frame ≤ 2,100 kg	
	D	• Sufficient strength of the structure of the front frame	
		Replaces issue of 5 April 2012	

Table 4.6. *The requirements list (2/2).*

Sandvik Mining		**Requirements list for a front frame**	**Issued on: 20 April 2012 Page:2/2**
Dates of changes	Demand /Wish	Requirements	Responsible
		5. Material	Aino-Maija Mylläri
	D	• Suitable in temperature range -40…+60°C	
	D	• Corrosion tolerant	
2 Jan	W	• Re-usable	
		6. Safety	
	D	• Operator under a roof during drilling	
2 Jan	D	• Good drilling stability	
2 Jan	D	• Good tramming stability	
	W	• Good tramming visibility	
	D	• Satisfactory tramming visibility	
	D	• Good drilling visibility	
		7. Ergonomics	
15 Dec	W	• Ergonomic operator environment	
		8. Production	
	W	• Easy to manufacture	
		9. Maintenance	
	W	• Easy to maintain	
15 Dec	W	• Long maintenance interval	
	W	• Easy to clean	
		10. Costs	
	W	• Profitable to manufacture	
		11. Regulation	
15 Dec	D	• Fulfillment of current standards and directives in the whole world	
15 Dec	W	• Fulfillment of standards and directives in the whole world in the future	
		12. Schedules	
	D	• Concept design ready by May 31, 2012	
26 Jan	W	• Concept design ready by April 24, 2012	
		Replaces issue of 5 April 2012	

After the requirements list has been created, a driller Kari Kumpumäki from Pyhäsalmi Mine was interviewed to validate the demands and wishes. Mr. Kumpumäki's answers support the created requirements list. The interview notes are shown in Appendix 6: Interview of a driller.

In addition, the requirements list is approved by two representatives from Sandvik Mining: Juha Piipponen (on 15 December 2011) and Martti Kansola (on 2 January 2012).

5. CONCEPT DESIGN

Now, that the task has been clarified, the development process moves on to concept design. The input of this phase is the requirements list created in task clarification. After several steps, one principal solution proposal is presented.

5.1. Abstracting

As mentioned in the theory part, the concept development phase will be accomplished mostly following Pahl et al.'s methods. According to Sub-section 2.3.2. the first step of concept development is abstracting.

First, personal opinions and irrelevant requirements are removed from the requirements list, after which the quantitative requirements are converted into qualitative ones. Then the remaining requirements are generalized and the problem is presented irrespective of any solution. The requirements list after these operations is presented in Table 5.1. below.

Table 5.1. *The abstracted requirements list.*

Sandvik Mining		**The abstracted requirements list for a front frame**	**Issued on: 23 April 2012 Page:1/1**
Dates of changes	Demand /Wish	Requirements	Responsible
	D	• Compact outside measures	
23 Apr	W	• Ability to drill inclined fans	
	D	• Wide drilling angles	
	D	• Stands the use and environment	Aino-Maija Mylläri
	D	• Operator under a roof during drilling	
	D	• Good stability	
19 Dec	D	• Fulfillment of standards and directives	
		Replaces issue of February 2012	

The requirements of the abstracted requirements list are summed up into one sentence that expresses the crux of the problem. The goal of this project is to develop the following object:

> *A compact, stable and durable front frame that fulfills standards and directives and enables varied and safety drilling.*

5.2. Function structure

It is now time to form the main function of the problem. Broadly thought the purpose of the front frame is to act as a connector between the boom module and the front carrier frame. The main function is presented in Figure 5.1. In the figure only material flow is defined. To clarify the main function and the function structure presented in Figure 5.2. the functions are written with red color.

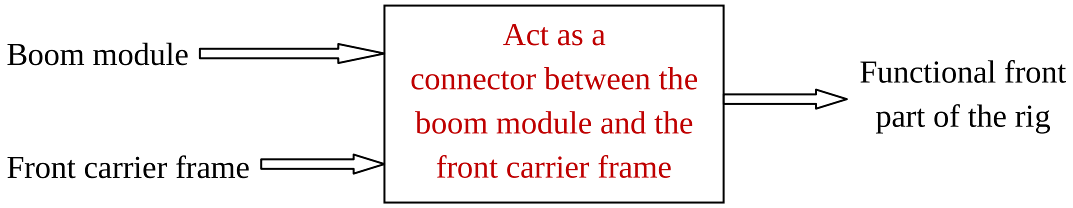


Figure 5.1. *The main function of the front frame.*

The main function can be divided into subfunctions using the requirements list. The function structure of the boom module is illustrated in Figure 5.2., where all the flows (except for bulk material, like screws, nuts, etc.) are visible.

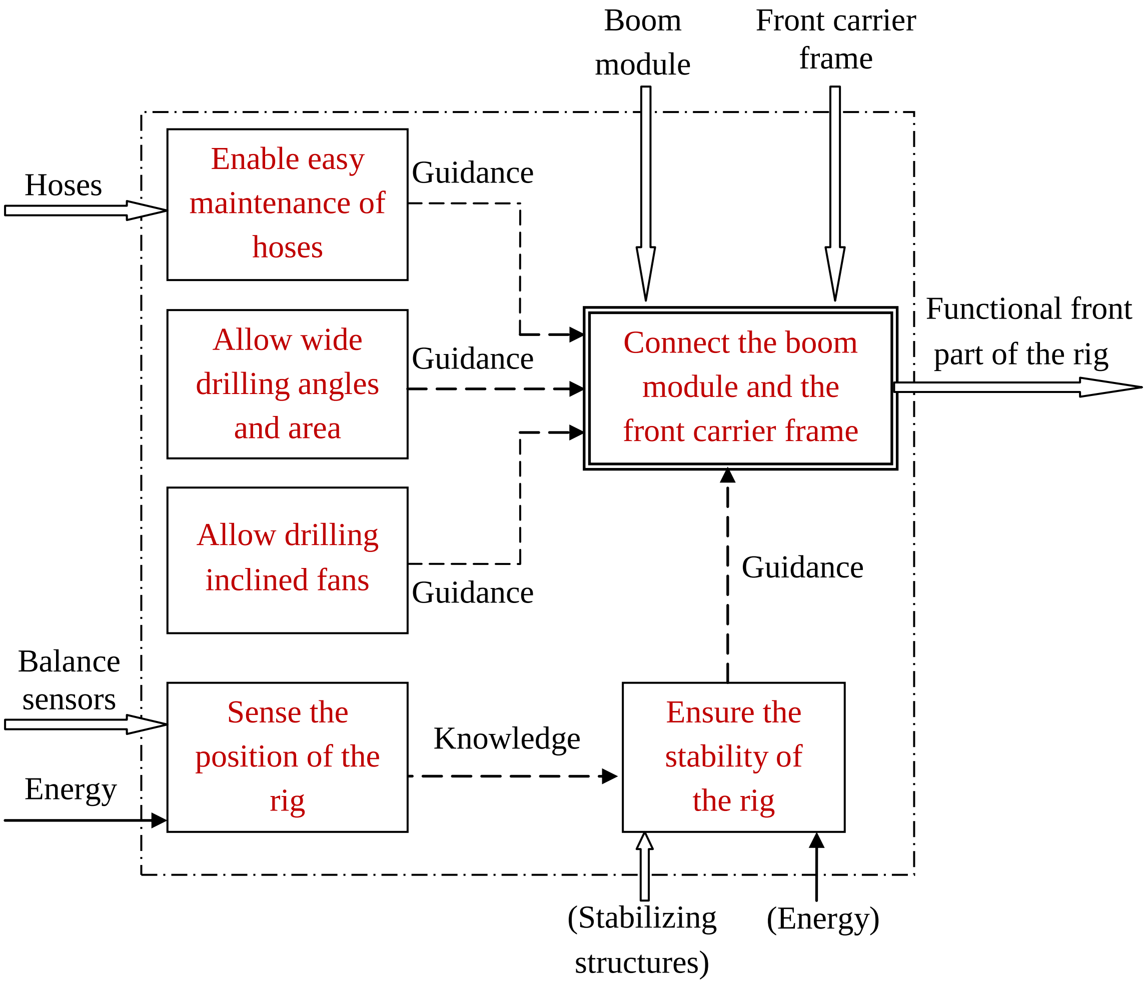


Figure 5.2. *The function structure of the front frame.*

As seen in Figure 5.2., the front frame has six functions: 1) enabling easy maintenance of hoses, 2) allowing wide drilling angles and area, 3) allowing drilling inclined fans, 4) sensing the position of the rig, 5) ensuring the stability of the rig and 6) connecting the boom module and the front carrier frame. The function number 6 is the main function of the front frame and according to the signal flows, functions 1-3 guide the main function. In addition to signal inputs, connecting parts (the boom module and the front carrier frame) are needed as inputs of material. Hoses are marked to be material input for enabling their maintenance.

Balancing the rig forms an own function chain, which begins from sensing the position and ends in ensuring the stability. Sensing demands sensors and energy. Knowledge about the position of the rig is needed to ensure the stability. The brackets around stabilizing structures and energy mean that the need for them depends on a working principle. In any case, ensuring the stability guides the main function.

5.3. Working principles

The next step in concept design is to search for working principles. Ideas are searched in a Tuplatiimi meeting described in Sub-section 2.5. In the Tuplatiimi meeting, nine participants developed rough sketches of the front frame. In addition to the writer of this thesis, the innovation group included eight employees from Sandvik's plant in Tampere. The names of the participants are presented in Appendix 7. The ideas of the sketches are gathered to the morphological matrix divided into subfunctions. Table 5.2. in the next two pages presents the morphological matrix.

Table 5.2. *The morphological matrix 1(3).*

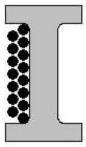
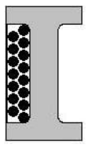
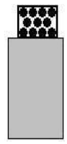
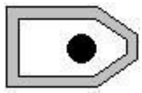
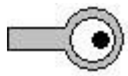
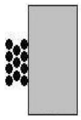
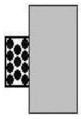
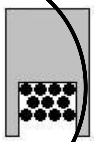
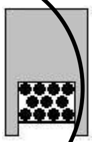
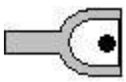
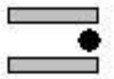
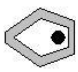
Solutions / *Subfunctions*	*A*	*B*	*C*	*D*
1. Enable easy maintenance of hoses	Hoses at the side of an I-beam  (uncovered)	Hoses at the side of an I-beam  (covered)	Hoses on top of a beam of a uniform section  (uncovered)	Hoses on top of a beam of a uniform section  (covered)
2. Allow wide drilling angles and area	A zooming front frame	A rising front frame	A trailer in the front	A rotating front frame
3. Allow drilling inclined fans	A joint between a front frame and a front carrier frame (a whole front frame turns)	A joint at some point of a front frame (a front frame turns)	A gear ring under a boom, turned by a motor (a boom turns)	A joint under a boom, turned by cylinders (a boom turns)
4. Sense the position of the rig	Balance sensors	Observation of an operator		
5. Ensure the stability of the rig	Jack beams	Zooming jack beams	Turning jack beams	Stingers
6. Connect the drill and the front carrier frame	A horseshoe shaped beam 	A single beam 	"A common hammerhead" 	A circle shaped beam 

Table 5.2. *The morphological matrix 2(3).*

Solutions / *Subfunctions*	*E*	*F*	*G*	*H*
1. Enable easy maintenance of hoses	Hoses at the side of a beam of a uniform section (uncovered) 	Hoses at the side of a beam of a uniform section (uncovered) 	Hoses under a beam (uncovered) 	Hoses under a beam (covered) 
2. Allow wide drilling angles and area	A shape of a front frame	A sideways moving front frame	A turning boom module	EFS (Extra feed swing) *
3. Allow drilling inclined fans	A joint under the boom, turned by a torque motor (a boom turns)	~~An alignment conducted by turning a front carrier frame (a front carrier frame turns)~~	A torque motor inside a boom (a drill turns)	
4.				
5. Ensure the stability of the rig	~~A drilling module located between a front and a rear module~~	Shape of a front frame	Extra tires under the drilling module	
6. Connect the drill and the front carrier frame	A fork shaped beam 	A U-shaped beam 	A rectangle shaped beam 	Two straight beams 

* Solution added on 6 February 2012

Table 5.2. *The morphological matrix 3(3).*

Solutions / *Subfunctions*	*I*	*J*	*K*	*L*
1.				
2.				
3.				
4.				
5.				
6. Connect the drill and the front carrier frame	"A salmiac shaped beam" 			

Before moving on to forming working structures, the solutions for subfunctions are evaluated and unsuitable solutions are marked to the morphological matrix. The solutions that are difficult to realize are crossed over and the solutions that can be used only in certain situations are circled. The explanations of the reasons for marking the cells are presented in the following Table 5.3.

Table 5.3. *Explanations for the marks in the morphological matrix.*

Solution	Explanation
1-G	Usable only with the raising front frame (solution 2-B)
1-H	Usable only with the raising front frame (solution 2-B)
2-F	Usable only with a single beam and common hammerhead (solutions 6-B and 6-C)
3-F	Walls of a drift often limit the turning angle between a front and rear modules
5-E	Demands large changes to the cabin and to the layout of the rig
5-G	Usable only with the trailer (solution 2-C)

5.4. Working structures

Working structures are now created by combining the solutions from the morphological matrix. The amount of possible combinations is huge: with the presented solution proposals there are 8×8×7×2×7×9 = 56,448 different combinations. Because of the huge amount of variants, only the most promising function structures are introduced. These combinations with a short structure description are gathered to Table 5.4. in the next page.

Table 5.4. *The most promising working structures in a random order.*

Structure	Combination	Description
a	1-D, 2-G, 3-G, 4-A, 5-A, 6-A	A horseshoe shaped beam version with a wide drilling area
b	1-C, 2-E, 3-B, 4-A, 5-A, 6-B	A single beam version with a joint at some point of the beam
c	1-F, 2-E, 3-A, 4-A, 5-A, 6-E	A fork version with jack beams
d	1-F, 2-E, 3-A, 4-B, 5-D, 6-E	A fork version with stingers
e	1-D, 2-B, 3-A, 4-A, 5-AB, 6-D	A raising and turning circle version with (zooming) jack beams
f	1-E, 2-B, 3-G, 4-A, 5-A, 6-C	A common hammerhead version with a raising front frame and jack beams
g	1-D, 2-E, 3-C, 4-A, 5-A, 6-A	A horseshoe shaped beam version with jack beams and a turning boom
h	1-A, 2-C, 3-A, 4-B, 5-G, 6-B	A single beam version with a trailer and extra tires
i	1-D, 2-E, 3-F, 4-A, 5-AE, 6-E	A version, in which the drilling module is located between a front and a rear modules
j	1-F, 2-E, 3-F, 4-A, 5-A, 6-A	A horseshoe shaped beam version with jack beams that is aligned by turning a front module
k	1-F, 2-E, 3-D, 4-AB, 5-B, 6-A	A horseshoe shaped beam version with zooming jack beams and a cylinder used joint under a boom
l	1-C, 2-AD, 3-B, 4-A, 5-A, 6-F	A U-shaped version with a zooming front frame
m	1-C, 2-A, 3-A, 4-A, 5-A, 6-G	A rectangle version with jack beams
n	1-C, 2-A, 3-A, 4-A, 5-C, 6-B	A single beam version with a zooming front frame and turning jack beams
o	1-C, 2-A, 3-A, 4-A, 5-A, 6-H	A two straight zooming beams version
p	1-D, 2-E, 3-E, 4-A, 5-B, 6-A	A horseshoe shaped beam version with zooming jack beams and a torque motor used joint under a boom
q	1-C, 2-E, 3-B, 4-A, 5-A, 6-F	A U-shaped version with a joint at some point of the beam
r	1-F, 2-BF, 3-B, 4-A, 5-B, 6-B	A rising and sideways sliding single beam version with zooming jack beams and a joint at some point of the beam
s	1-D, 2-E, 3-C, 4-A, 5-B, 6-I	A salmiac shaped version with zooming jack beams and a gear ring
t	1-E, 2-BF, 3-C, 4-A, 5-B, 6-B	A single beam version with zooming jack beams, a rising and sliding front frame and a gear ring

5.5. Finding suitable combinations

A preliminary evaluation is performed in Table 5.5. below.

Table 5.5. *The selection chart for the working structures.*

Sandvik Mining	SELECTION CHART for working structures								Page: 1/1
Solution variants evaluated by SELECTION CRITERIA (+) Yes (–) No (?) Lack of information (!) Check requirements list								DECISION Mark solution variants (+) Pursue solution (–) Eliminate solution (?) Collect information (re-evaluate solution) (!) Check requirements list for changes	
Working structures	A Compatibility assured	B Fulfills demands of requirements	C Realizable in principle	D Within permissible costs	E Incorporates direct safety measures	F Preferred by designer's company	G	Remarks (Indications, Reasons)	DECISION
a	+	+	+	+	+	+			+
b	+	+	+	+	+	+			+
c	+	+	+	+	+	+			+
d	+	+	+	+	+	?		Difference to c: jack beams → stingers	–
e	+	+	+	+	+	+			+
f	+	+	+	+	+	+			+
g	+	+	+	+	+	+			+
h	+	+	+	+	+	+			+
i	–	+	+	–	+	+		Demands radical changes to the layout	–
j	+	–	+	+	+	+		Too wide while drilling inclined fans	–
k	+	+	+	+	+	+			+
l	?	+	+	+	+	–			–
m	+	+	+	+	+	–			–
n	+	+	+	+	+	–			–
o	?	+	+	+	+	–			–
p	+	+	+	+	+	–		Difference to k: cylinder → torque motor	–
q	+	+	+	+	+	–			–
r	+	+	+	+	+	?			+
s	+	+	+	+	+	–			–
t	+	+	+	+	+	?			+
Date: 23 Dec, 2011	Initials: A-MM								

The preliminary evaluation was conducted to limit the amount of working structures and to find the best combinations. After the preliminary evaluation, 10 combinations are left. A crude sketching is performed for the left-standing combinations to investigate whether the solutions are realizable in practice or not. The crude sketching shows that all 10 combinations can be realized. However, one significant remark is made during the sketching, based on which the following change to the combination e is done:

- A round shape is not functional
  - → in the combination e the shape of a front frame is changed to a fork shape

5.6. Evaluation

Now that the preliminary evaluation is completed the actual evaluation can be started. The purpose of the evaluation is to choose the best working structure.

5.6.1. Establishing and weighting the evaluation criteria

First, the evaluation criteria must be established and weighted. The criteria are set on the grounds of the requirements list, the main headings presented in page 16 and an example in *Engineering Design: A Systematic Approach* (Pahl et al. 2007, p. 223). The criteria and their weightings are defined in the objective tree in Figure 5.3. in the next page. In Figure 5.3. the final criteria weightings are **bolded**.

It should be noted that the criteria are not completely independent from each other. This decreases the reliability of the evaluation and supports using verbal values. The possibility of drilling inclined fans is not included in the objective tree as it is a demand that every combination fulfills.

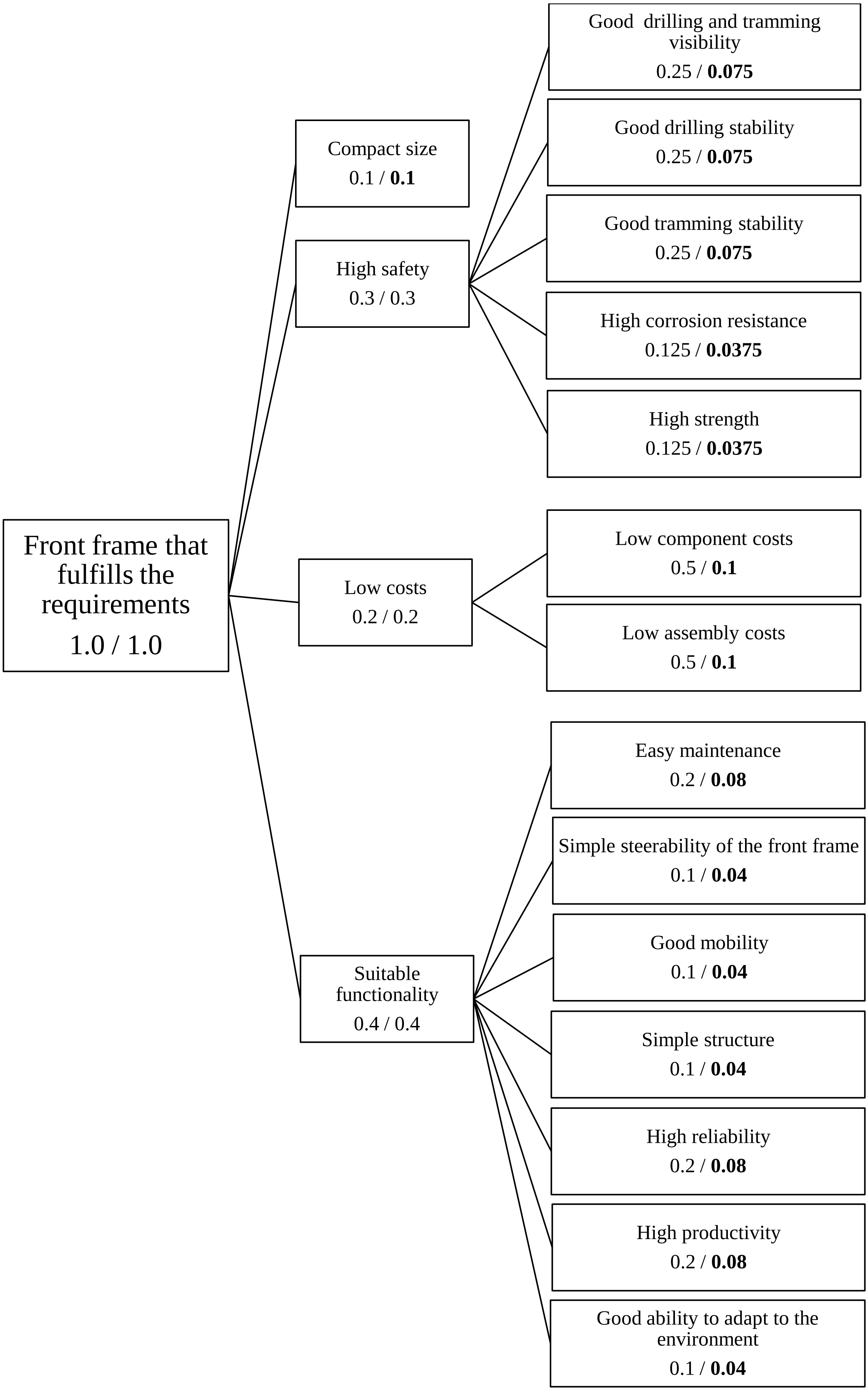


Figure 5.3. *The objective tree of the weighted criteria.*

There are altogether 15 criteria in the objective tree. The weightings vary between 0.0375 and 0.1, compact size and costs reaching the highest weightings. The size affects for example tramming agility and the weight, and thus the high weighting is reasoned.

5.6.2. Setting and valuing the parameters

First, the corresponding objective parameters for the criteria are defined. In most cases the parameter is the same as the criterion but in some cases they differ from each other. Objective parameters are shown in Table 5.6.

Table 5.6. *The criteria and corresponding parameters.*

Number	Criterion	Objective parameter
1	Compact size	Size of the front frame
2	Good drilling and tramming visibility	Visibility during drilling and tramming
3	Good drilling stability	Risk of the rig falling over while drilling
4	Good tramming stability	Risk of the rig falling over while tramming
5	High corrosion resistance	Corrosion resistance
6	High strength	Strength of the front frame
7	Low component costs	Price of the main components
8	Low assembly costs	Easiness of assembly
9	Easy maintenance	Easiness of maintenance
10	Simple steerability of the front frame	Easiness of moving the front frame
11	Good mobility	Agility of the rig
12	Simple structure	Simplicity of the structure of the front frame
13	High reliability	Level of reliability
14	High productivity	Level of productivity
15	Good ability to adapt to the environment	Ability to adapt to the environment

The next task is to value the parameters on the scale of 0…4. Verbal values are used widely, because it is troublesome to define exact numerical values. The fact that not all the criteria are independent from each other is another reason for using not so exact values. The parameters and values are gathered to Table 5.7. in the next two pages.

Table 5.7. *The parameters and values for the criteria 1(4).*

Points VDI 2225	Parameter magnitudes			
	Size of the front frame (-)	Visibility during drilling and tramming(-)	Risk of the rig falling over while drilling (-)	Risk of the rig falling over while tramming (-)
0	Substantially larger than in current DL421	Extremely poor	Major, even on a flat ground	Extremely major
1	Larger than in current DL421	Poor	Major on a grainy ground	Major
2	Equal to current DL421	Average	Average	Average
3	Smaller than current DL421	Good	Minor on a flat ground	Minor
4	Substantially smaller than in current DL421	Excellent	Minor, even on a grainy ground	Extremely minor

Table 5.7. *The parameters and values for the criteria 2(4).*

Points VDI 2225	Parameter magnitudes			
	Corrosion resistance (-)	Strength of the front frame (-)	Price of the main components (-)	Easiness of assembly (-)
0	Extremely poor	Extremely poor	Substantially higher than in current DL421	Extremely troublesome
1	Poor	Poor	Higher than in current DL421	Troublesome
2	Average	Average	Equal to current DL421	Average
3	Good	Good	Lower than in current DL421	Easy
4	Excellent	Excellent	Substantially lower than in current DL421	Extremely easy

Table 5.7. The parameters and values for the criteria 3(4).

Points VDI 2225	**Parameter magnitudes**			
	Easiness of maintenance (-)	Easiness of moving the front frame (-)	Agility of the rig (-)	Simplicity of the structure of the front frame (-)
0	Extremely troublesome	Extremely troublesome	Extremely poor	Extremely complicated
1	Troublesome	Troublesome	Poor	Complicated
2	Average	Average	Average	Average
3	Easy	Easy	Good	Simple
4	Extremely easy	Extremely easy	Excellent	Extremely simple

Table 5.7. The parameters and values for the criteria 4(4).

Points VDI 2225	**Parameter magnitudes**			
	Level of reliability (-)	Level of productivity (-)	Ability to adapt to the environment (-)	
0	Extremely low	Extremely low	Extremely poor	
1	Low	Low	Poor	
2	Average	Average	Average	
3	High	High	Good	
4	Extremely high	Extremely high	Excellent	

5.6.3. Evaluating the working structures

The working structures that passed the preliminary evaluation are now valued and pointed based on the combination and crude sketching. The results are shown in Tables 5.8.-5.11. and Figures 5.4.-5.7. in the following pages. The criteria and the objective parameters used in Table 5.8.-5.11. are shown in Table 5.6. The crude models of the structures are presented below the tables to offer the reader a better conception of them.

Table 5.8. *The evaluation chart 1(4).*

Evaluation criteria		**Objective parameters**		**Working structure a**		**Working structure b**		**Working structure c**	
Criterion	Weight	Parameter	Unit	Value	Weighted value	Value	Weighted value	Value	Weighted value
1	0.1	1	-	2	0.20	4	0.40	3	0.30
2	0.075	2	-	2	0.15	3	0.225	2	0.15
3	0.075	3	-	3	0.225	3	0.225	4	0.30
4	0.075	4	-	3	0.225	3	0.225	3	0.225
5	0.0375	5	-	2	0.075	4	0.15	4	0.15
6	0.0375	6	-	2	0.075	4	0.15	4	0.15
7	0.1	7	-	1	0.10	4	0.40	3	0.30
8	0.1	8	-	2	0.20	4	0.40	4	0.40
9	0.08	9	-	2	0.16	4	0.32	3	0.24
10	0.04	10	-	3	0.12	4	0.16	4	0.16
11	0.04	11	-	2	0.08	3	0.12	2	0.08
12	0.04	12	-	1	0.04	4	0.16	3	0.12
13	0.08	13	-	3	0.24	3	0.24	4	0.32
14	0.08	14	-	3	0.24	4	0.32	4	0.32
15	0.04	15	-	2	0.08	3	0.12	2	0.08
	$\sum = 1$			$\sum = 33$	**$\sum = 2.21$**	$\sum = 54$	**$\sum = 3.615$**	$\sum = 49$	**$\sum = 3.295$**

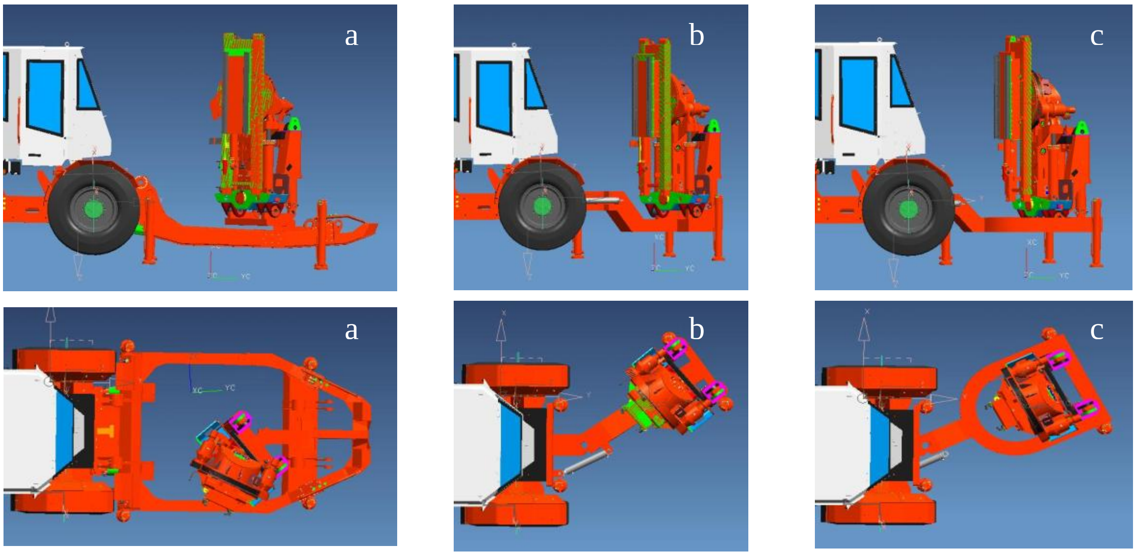


Figure 5.4. *The crude models of the working structures: left Structure a from the side and from above, in the middle Structure b and right Structure c.*

Table 5.9. *The evaluation chart 2(4).*

Evaluation criteria		**Objective parameters**		**Working structure e**		**Working structure f**		**Working structure g**	
Criterion	Weight	Parameter	Unit	Value	Weighted value	Value	Weighted value	Value	Weighted value
1	0.1	1	-	3	0.30	4	0.40	2	0.20
2	0.075	2	-	2	0.15	3	0.225	2	0.15
3	0.075	3	-	4	0.30	4	0.30	4	0.30
4	0.075	4	-	3	0.225	3	0.225	3	0.225
5	0.0375	5	-	4	0.15	4	0.15	2	0.075
6	0.0375	6	-	4	0.15	4	0.15	2	0.075
7	0.1	7	-	3	0.30	3	0.30	1	0.10
8	0.1	8	-	4	0.40	3	0.30	2	0.20
9	0.08	9	-	3	0.24	3	0.24	3	0.24
10	0.04	10	-	3	0.12	3	0.12	4	0.16
11	0.04	11	-	2	0.08	3	0.12	2	0.08
12	0.04	12	-	3	0.12	4	0.16	2	0.08
13	0.08	13	-	4	0.32	2	0.16	3	0.24
14	0.08	14	-	4	0.32	4	0.32	3	0.24
15	0.04	15	-	3	0.12	3	0.12	2	0.08
	$\sum = 1$			$\sum = 49$	$\boldsymbol{\sum = 3.295}$	$\sum = 50$	$\boldsymbol{\sum = 3.29}$	$\sum = 37$	$\boldsymbol{\sum = 2.445}$

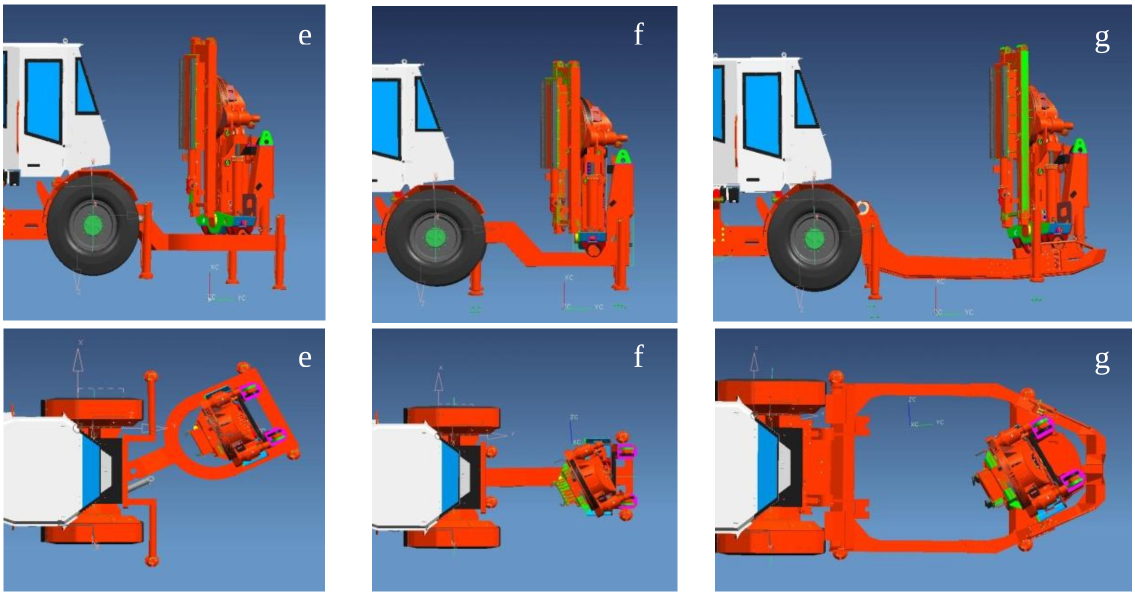


Figure 5.5. *The crude models of the working structures: left Structure e from the side and from above, in the middle Structure f and right Structure g.*

Table 5.10. The evaluation chart 3(4).

Evaluation criteria		Objective parameters		Working structure h		Working structure k		Working structure r	
Criterion	Weight	Parameter	Unit	Value	Weighted value	Value	Weighted value	Value	Weighted value
1	0.1	1	-	4	0.40	2	0.20	4	0.40
2	0.075	2	-	3	0.225	2	0.15	3	0.225
3	0.075	3	-	2	0.15	4	0.30	4	0.30
4	0.075	4	-	3	0.225	3	0.225	2	0.15
5	0.0375	5	-	4	0.15	2	0.075	4	0.15
6	0.0375	6	-	4	0.15	2	0.075	4	0.15
7	0.1	7	-	4	0.40	1	0.10	3	0.30
8	0.1	8	-	4	0.40	2	0.20	4	0.40
9	0.08	9	-	3	0.24	3	0.24	3	0.24
10	0.04	10	-	2	0.08	4	0.16	3	0.12
11	0.04	11	-	4	0.16	2	0.08	4	0.16
12	0.04	12	-	3	0.12	2	0.08	3	0.12
13	0.08	13	-	2	0.16	4	0.32	3	0.24
14	0.08	14	-	3	0.24	3	0.24	3	0.24
15	0.04	15	-	2	0.08	3	0.12	4	0.16
	$\sum = 1$			$\sum = 47$	**$\sum = 3.18$**	$\sum = 39$	**$\sum = 2.565$**	$\sum = 51$	**$\sum = 3.355$**

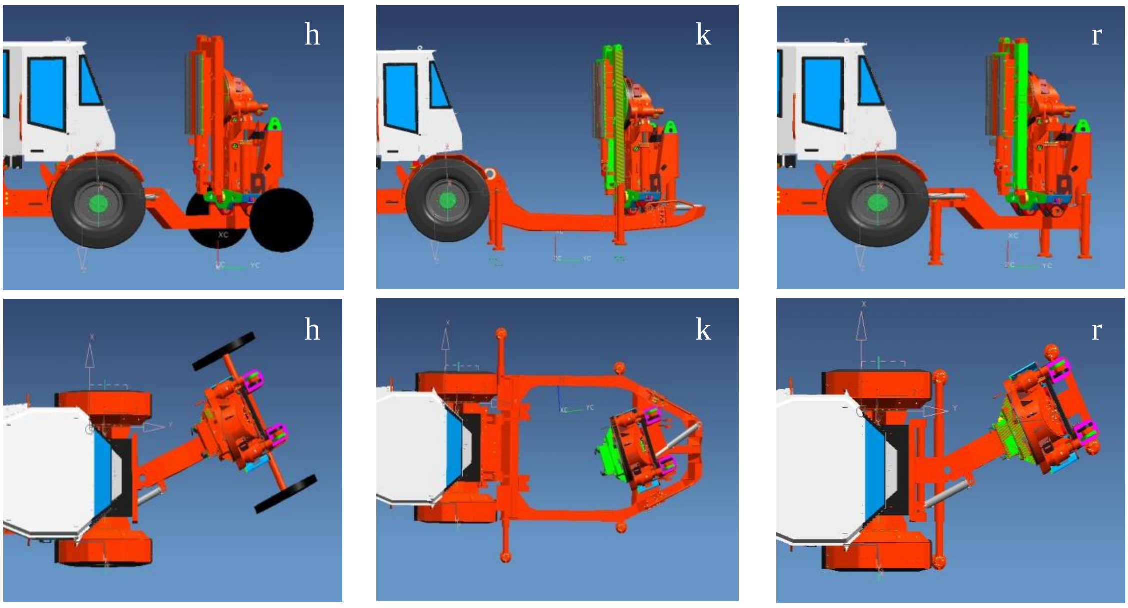


Figure 5.6. *The crude models of the working structures: left Structure h from the side and from above, in the middle Structure k and right Structure r.*

Table 5.11. *The evaluation chart 4(4).*

Evaluation criteria		**Objective parameters**		**Working structure t**	
Criterion	Weight	Parameter	Unit	Value	Weighted value
1	0.1	1	-	4	0.40
2	0.075	2	-	3	0.225
3	0.075	3	-	4	0.30
4	0.075	4	-	3	0.225
5	0.0375	5	-	4	0.15
6	0.0375	6	-	4	0.15
7	0.1	7	-	3	0.30
8	0.1	8	-	4	0.40
9	0.08	9	-	3	0.24
10	0.04	10	-	3	0.12
11	0.04	11	-	4	0.16
12	0.04	12	-	3	0.12
13	0.08	13	-	2	0.16
14	0.08	14	-	3	0.24
15	0.04	15	-	4	0.16
	∑=1			∑=51	**∑=3.35**

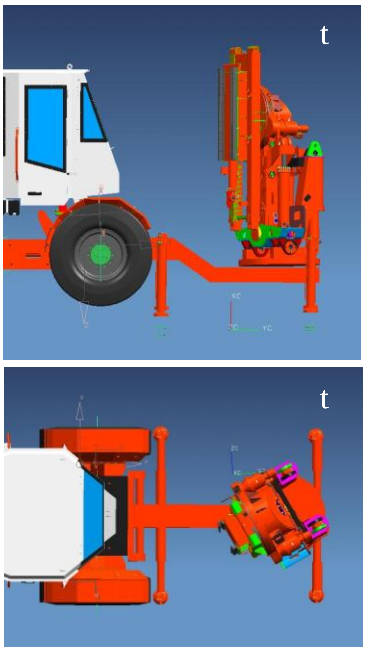


Figure 5.7. *The crude model of the Working structure t.*

5.6.4. Comparing the working structures and identifying uncertainties

According to the evaluation performed in the previous sub-section the working structures b, c, e, f, h, r and t achieved a score over 3.0. The theoretical maximum score of the evaluation was 4.0. All the combinations with the horseshoe shaped front frame (structures a, g and k) reached a score under 3.0 and analyzing them further is unnecessary.

From the front frame types the single beam reached the positions one, two and three. According to the evaluation, structure b was the best combination with the score of 3.615, structure r the second best with the score of 3.355 and structure t the third best with a score of 3.35. These three working structures are moved forward to value profile creation.

Structures c and e are largely similar combinations and they reached an equal score (3.295) in the evaluation. In the combination e jack beams can be zoomed and the front frame is rising, whereas structure c does not have these features. Because of the similarity, only the more diversified structure e continues to value profile creation.

The “common hammerhead” structure (combination f) reached a score of 3.29, and achieved the sixth highest rate in the evaluation. The shape of the “common hammerhead” is largely similar to the single beam and combination f is moved to value profile creation.

Structure h differs from the other structures by having tires under the drilling module. It also reached to a score over 3.0 by scoring at 3.18. For the reason of being different it is taken to value profile creation to offer a diverging solution to the problem of stability.

Altogether six structures are moved to value profile creation. The amount is rather big but can be justified as the uncertainty of the evaluation is fairly big as well. The uncertainty results from several variables. First, the crude models are truly just rough drafts and the values in the evaluation charts are all estimations. Second, the criteria affect the results largely. Differently chosen and weighted criteria could possibly give a totally different result. Some criteria also have fairly strong dependency on each other. For example high corrosion resistance improves strength, simple structure eases assembly lowering assembly costs and easy maintenance dilutes reliability. The third large uncertainty factor is subjectivity. The evaluation was realized by one person only and this inevitably leads to subjectivity.

At this point, the evaluation is reviewed together with the technical tutor of this thesis, Martti Kansola, to verify and validate the process. Based on the conversation with Mr. Kansola, some of the weightings of the criteria were modified. The objective tree shown in page 59 and Tables 5.8.-5.11. are the refreshed versionsj. Another remarkable information that came up during the meeting with Mr. Kansola was the needlessness of the sideways sliding front frame. The satisfactory width of parallel holes can also be achieved without this feature.

5.6.5. Creating value profiles

The next task is to create value profiles from six concept candidates that were mentioned in the previous sub-section to be moved forward to the next stage. The aim of this task is to visualize the strengths and weaknesses of the concept candidates, after which ways to improve the weaknesses are searched. The weak points are replaced with more valuable solutions, if the change does not affect the basic idea of the structure or significantly weaken other features. Figures 5.8-5.10. illustrate two structures each. In contrast to the value profiles presented by Pahl et al. (see Figure 2.12. in page 18) the weightings are not shown in the following figures.

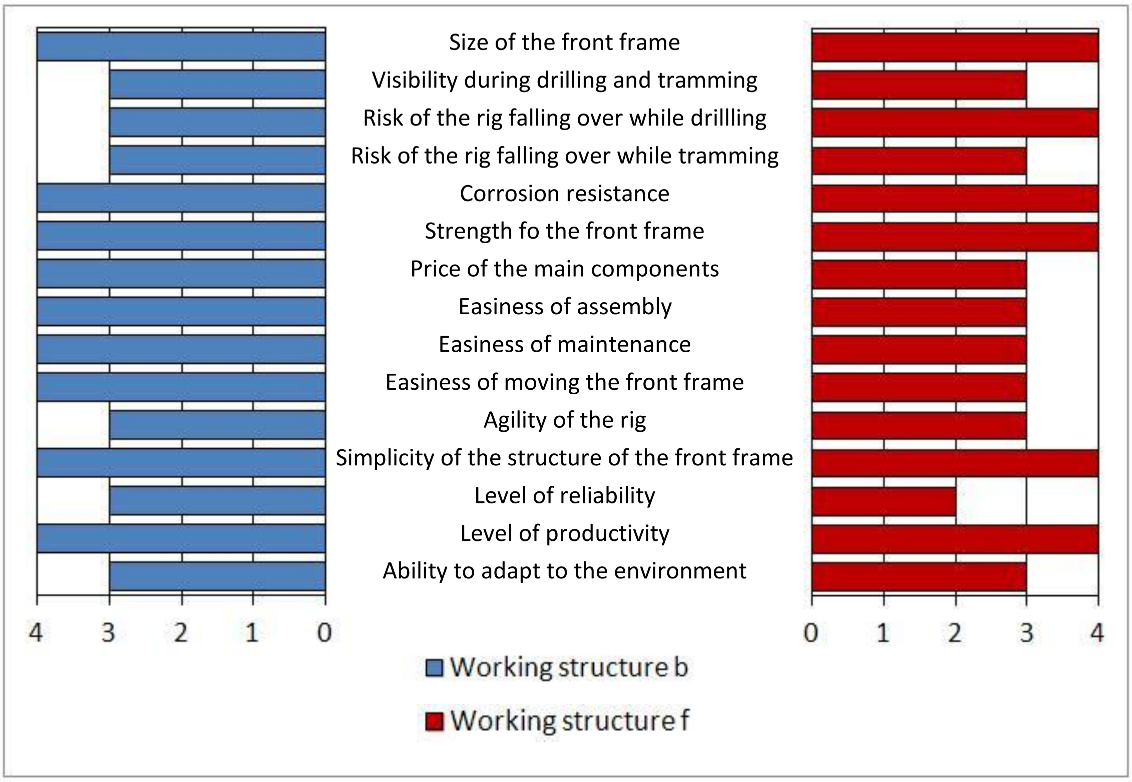


Figure 5.8. *The value profiles of Structure b (left) and Structure f (right).*

The first value profile (Figure 5.8.) demonstrates the values of the working structures b and f. Structure b reached the highest score in the evaluation and according to Figure 5.8. it has no significant weak spots. Structure b received only values 3 and 4. Value 3 is reached in five points. There are no simple solutions to improve visibility or mobility, but reliability can be increased by adding covers on the hoses and adaptability would improve if the simple jack beams were replaced with the zooming ones. However, adding covers decreases easiness of assembly. Tramming stability could also be improved by a software application that would inhibit tramming when the front frame is turned.

Structure f, in turn, receives value 2 in one point and value 3 in eight points (see Figure 5.8.). The most significant weaknesses of Structure f are found in reliability and ability to adapt to the environment. The torque motor inside the boom is not as reliable as a simple joint. In addition, in case of a torque engine failure, repairing would require disassembly of the boom. The engine is also more exposed to dust and humidity as it is located close to the drill. These problems can't be solved without changing the basic principle of the structure. From the points that reached the value 3 only ability to adapt to the environment can be easily improved. Exactly like in Structure b, adaptability can be increased by replacing the simple jack beams with the zooming ones.

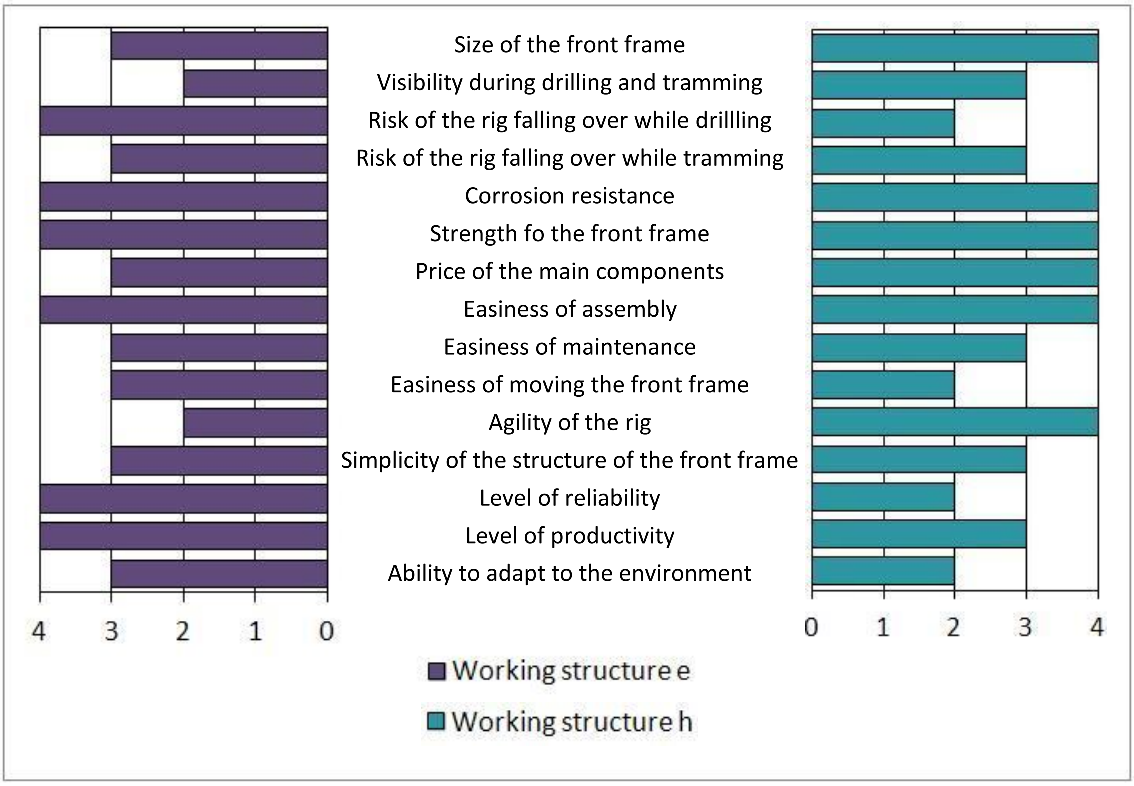


Figure 5.9. *The value profiles of Structure e (left) and Structure h (right).*

The next structures to be illustrated as the value profiles are structures e and h. The value profiles are visible in Figure 5.9. Structure e reaches value 2 in two points: in visibility and agility. The width of the front frame causes these weaknesses and improving them is not possible without changing the basic structure. From the points of the value 3, size, tramming stability, price, easiness of moving the front frame and simplicity of the structure can neither be improved with the chosen solutions. Adaptability could be increased by enabling the sideways sliding of the front frame, but as mentioned earlier, it is needlessness. Maintenance can be eased by removing the covers of the hoses. However, this change decreases reliability.

The biggest weaknesses of Structure h are found from drilling stability, easiness of moving the front frame, reliability and adaptability. The basic idea of this combination is that the drilling module lies on a trailer. The trailer has two tires and it does not rise off the ground. The trailer might be slightly unstable while drilling on an uneven ground as the trailer is impossible to balance (compare with jack beams). Thus, drilling stability can’t be improved without radical changes to the structure. The fact that the trailer does not rise off the ground makes the drilling module difficult to move, as the whole rig must be moved to be able to move the drill. In addition, the tires and the axle between them are the reasons for the poor values of reliability and adaptability. Again, these disadvantages can’t be fixed without losing the basic idea of the candidate. From the points that reached the value 3, only easiness of maintenance can be improved by adding covers on hoses and it is possible only at reliability’s expense.

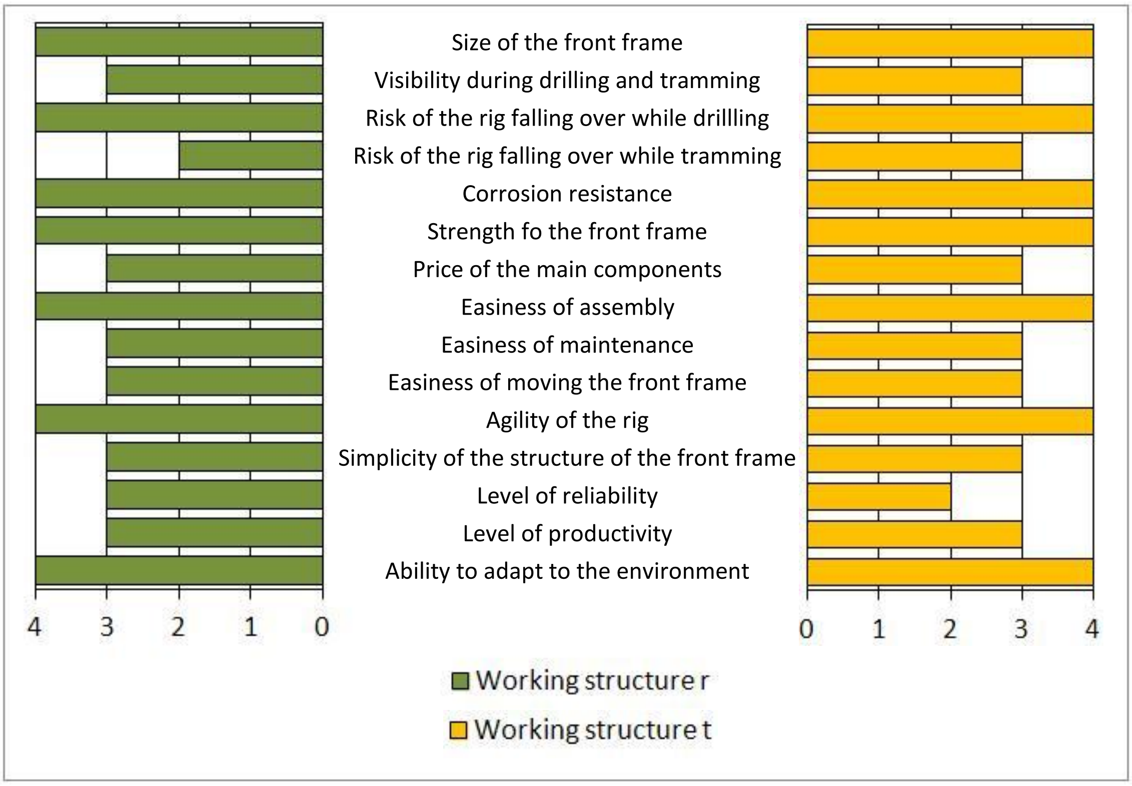


Figure 5.10. *The value profiles of Structure r (left) and Structure t (right).*

The value profiles of the remaining structures r and t are presented in Figure 5.10. In both structures the front frame is a straight beam. The biggest difference between the structures is the solution that enables drilling inclined fans. Structure r has got a joint at some point of the front frame, whereas structure t has a gear ring under the drilling module. The turning front frame increases the risk of the rig falling over during tramming, if tramming is possible when the front frame is turned. Like in structure b this problem can be solved by a software application. A beam, that enables the front frame to slide sidewise, increases the price of the main components. In addition, the beam decreases easiness of maintenance and moving the front frame, simplicity of the structure, reliability and productivity. These disadvantages can be eliminated by removing the beam. As mentioned earlier, the feature of sliding sideways is unnecessary, thus removing the beam is not a problem.

Structure t has its largest weak spot in reliability. Reliability problem originates from the sidewise movement of the front frame, the uncovered hoses and the gear ring.

Like in structure r, the beam, that enables the sidewise movement, can be removed. Besides improving reliability, removing the beam would also lower the price of the main components, simplify the structure of the front frame, improve tramming safety and productivity and increase easiness of maintenance and moving the front frame. Hoses can also be covered to improve reliability, but only at the expense of easiness of maintenance. Rotating the gear ring can be performed by an electric or a hydraulic motor. Dusty and humid conditions close to the drill diminish reliability of working of a motor. In addition, rotation is not continuous and the rotating angle is only ±35°. A gear also needs maintenance in a form of lubrication. Thus the need of a gear is dubious. The turning movement could also be executed without gears, by means of hydraulic cylinders. This solution would eliminate the need for a motor but steering accuracy would bring challenges for the implementation of the cylinder system.

At this point, two working structures are chosen and, if possible, improved. On the grounds of the value profiles presented and analyzed above, structures b, r and t seem to be the best alternatives. The combinations b and r and largely similar and thus only structure b, having reached a higher score in the evaluation, is selected for the iteration round 1.

5.7. Iteration: round 1

Working structures b and t are chosen for the first iteration round. The combinations are modified and then re-evaluated to ensure that the changes actually improved the working structures.

5.7.1. Modifying and re-evaluating the chosen working structures

The combinations that are chosen for the re-evaluation are structures b and t. According to the analysis of the value profile, the following changes are made to structure b:

- Hoses on top of the beam are covered (1-C → 1-D).
- A software application, that inhibits tramming when the front frame is turned, is added to the structure (4-A → 4-A + a soft ware application).
- Jack beams are replaced with zooming jack beams (5-A → 5-B).

After the changes the final combination of structure b is renamed to structure X and its combination is: 1-D, 2-E, 3-B, 4-A+software application, 5-B, 6-B.

Structure t, in turn, undergoes the following changes:

- Hoses at the side of the beam are covered (1-E → 1-F).
- A beam, which enables the sidewise movement, is removed (2-BF → 2-B).
- Hydraulic cylinders are added to be an alternative solution for a gear ring (3-C → 3-C/D).

The last change splits the working structure in two different working structures that are named to Structure Y and Structure Z. The combinations of the new structures are: 1-F, 2-B, 3-C, 4-A, 5-B, 6-B (Structure Y) and 1-F, 2-B, 3-D, 4-A, 5-B, 6-B (Structure Z).

These three newborn structures are now roughly modeled and evaluated with the same criteria and weightings as the original structures. Table 5.12. presents the values that the alternatives reach and Figure 5.11. in the next page shows their rough models.

Table 5.12. *The evaluation chart of the improved structures.*

Evaluation criteria		**Objective parameters**		**Working structure X**		**Working structure Y**		**Working structure Z**	
Criterion	Weight	Parameter	Unit	Value	Weighted value	Value	Weighted value	Value	Weighted value
1	0.1	1	-	4	0.40	4	0.40	4	0.40
2	0.075	2	-	3	0.225	3	0.225	3	0.225
3	0.075	3	-	3	0.225	4	0.30	4	0.30
4	0.075	4	-	4	0.30	4	0.30	4	0.30
5	0.0375	5	-	4	0.15	4	0.15	4	0.15
6	0.0375	6	-	4	0.15	4	0.15	4	0.15
7	0.1	7	-	3	0.30	3	0.30	4	0.40
8	0.1	8	-	4	0.40	4	0.40	4	0.40
9	0.08	9	-	3	0.24	3	0.24	3	0.24
10	0.04	10	-	4	0.16	3	0.12	3	0.12
11	0.04	11	-	3	0.12	3	0.12	3	0.12
12	0.04	12	-	4	0.16	4	0.16	4	0.16
13	0.08	13	-	4	0.32	3	0.24	4	0.32
14	0.08	14	-	4	0.32	4	0.32	4	0.32
15	0.04	15	-	4	0.16	4	0.16	4	0.16
	$\sum = 1$			$\sum = 55$	$\sum = \mathbf{3.63}$	$\sum=54$	$\sum=\mathbf{3.585}$	$\sum=56$	$\sum=\mathbf{3.765}$

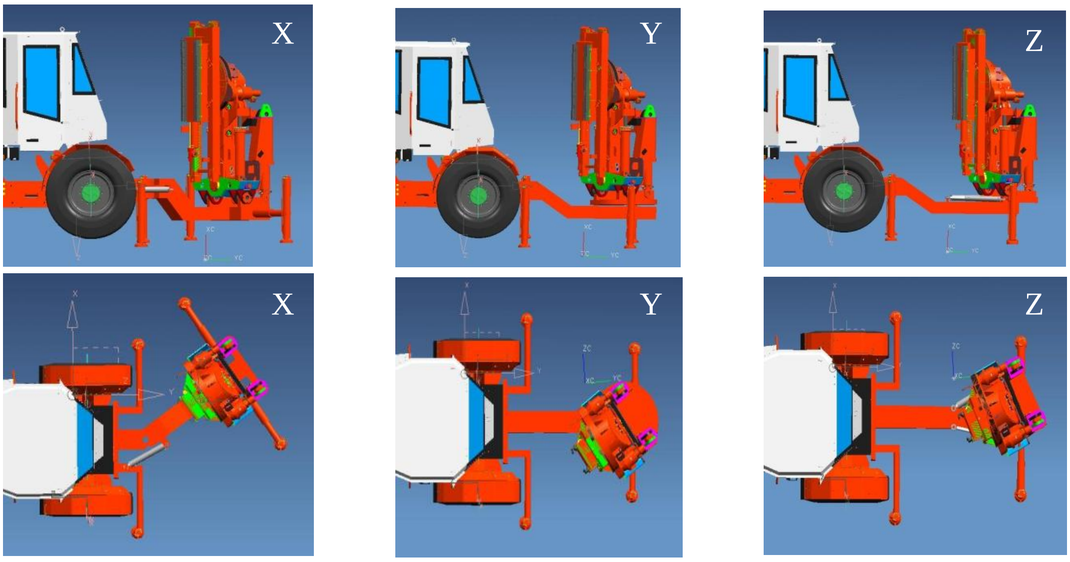


Figure 5.11. *The crude models of the working structures: left Structure X from the side and from above, in the middle Structure Y and right Structure Z.*

All improved concepts reach a higher score than their original concept proposals. The improvements are thus successful. Regardless of the re-evaluation, the uncertainties have not disappeared but remain the same as in the first evaluation (see Sub-section 5.6.4. *Comparing the working structures and identifying uncertainties*). The values are presented graphically in Figure 5.12. As there are only three concepts, they are all shown in Figure 5.12.

Figure 5.12. *The value profiles of the improved structures X, Y and Z.*

According to the value profiles shown in Figure 5.12. there are no significant weak points in any of the structures. Stability of the turning front frame (structure X) may, however, be problematic. The turning boom (structures Y and Z), instead, may face troubles with hosing. In addition, the reliability of a motor (structure Y) and functionality of cylinders (structure Z) must be established.

At this point, however, it appears that a smaller size class of the production drill rig family must also be taken into consideration in concept development. For that reason, a second iteration round is needed.

5.8. Iteration: round 2

Models DL311 and DL321 belong to the same product family with 401-series. The rigs of the 301-series are smaller and they have slightly different area of usage and thus slightly different demands than DL411 and DL421. The most important demand of DL311 and DL321 is introduced next.

5.8.1. Special need of DL311 and DL321

The most significant difference between the 301- and 401-series is in directions of the drilling holes. Parallel holes are common with DL311 and DL321, whereas DL411 and DL421 are mainly used for fan drilling. Because of favoring parallel holes, it is significantly important to get close to the walls with the 301-series rigs. Figure 5.13. below presents the minimum distances between a vertical hole and a wall.

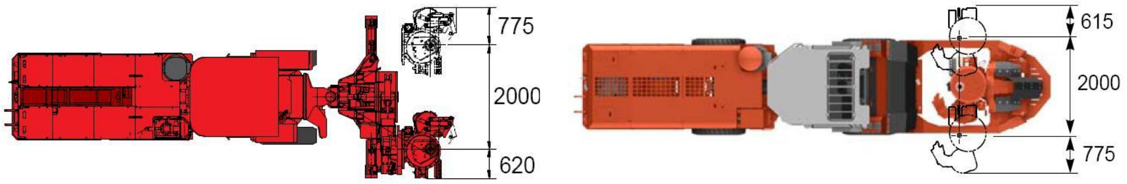


Figure 5.13. *Minimum distances between a vertical hole and a wall. Left DL311 and right DL321. (Figure modified from: Technical Specification, DL311-7; Technical Specification, DL321-7C)*

According to Figure 5.13. the minimum distances between a vertical hole and a wall in DL311 and DL321 are different than those in DL411 and DL421 (see Figures 4.3. and 4.7.). Especially the distance at the rod retainer side is significantly smaller in 300-series than in 400-series (775 mm versus 1,030 mm). In addition, EFS (Extra feed swing) can be chosen as an option to DL311 to decrease the distances to 530 mm at both sides (Technical Specification, Extra feed swing). The minimum distances between a wall and a vertical hole with EFS are shown in Figure 5.14. in the next page.

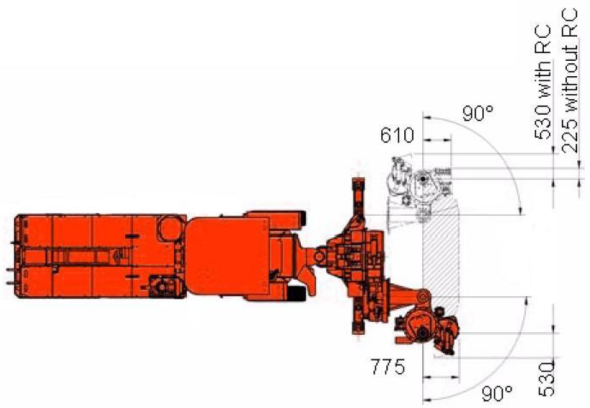


Figure 5.14. *Minimum distances between a vertical hole and a wall of DL311 with EFS (Figure modified from: Technical Specification, Extra feed swing).*

The need of drilling vertical holes close to the walls is added to the list of specifications although it is not a demand of 401-series rigs. Table 5.13. shows the addition of the distance.

Table 5.13. *The list of specifications added with the demand from 301-series.*

Metric number	Metric/demand/wish	Unit/ W/D	DL411	DL421
1	Tramming length	mm	9,400	11,250
…				
24	Distance between a vertical hole and a wall	mm	1,030/650 (DL311): 775/620	1,030/650 (DL311): 775/620

The benchmarking information for these distances was not available. The demand must also be added for the requirements list. It is unnecessary to present the whole requirement list again and for that reason only the added demand is shown in Table 5.14.

Table 5.14. *The addition to the requirements list.*

Sandvik Mining		**Requirements list for a front frame**	**Issued on: 6 February 2012 Page:1/2**
Dates of changes	Demand /Wish	Requirements	Responsible
6 Feb	D	*3. Drilling area* • … • Distance between a vertical hole and a wall as small as possible • …	Aino-Maija Mylläri
		Replaces issue of 6 February 2012	

The added demand affects neither the function structure nor the objective tree as it can be included to the function *Allow wide drilling angles and area* and to the criterion *Good ability to adapt to the environment*.

5.8.2. Modifying and re-evaluating the chosen structures

None of the chosen three variants can get close enough to the wall to fulfill the demand of the 301-series. Adding EFS for the structures would turn the drill next to the wall. A picture of EFS can be seen in Figure 5.15. The addition has both positive and negative influences on the characteristics of the rig. The possibility to add EFS as an option can be seen as a positive feature. There is no need to get close to the wall with DL411s and DL421s, and thus the solution that can be easily realized as an option is preferable. On the other hand, adding EFS demands a longer or an extendable beam for the front frame. Visibility may also become a problem with the EFS. A driller should see the drill and the drill bit on the wall but, if the drilling module is turned 90°, the visibility deteriorates. Though, exploiting cameras or mirrors would decrease this problem.

Figure 5.15. *An EFS in DL311 (Figure modified from: Technical Specification, Extra feed swing).*

Concept proposals X, Y and Z are now modified to fulfill the demand of the 301-series as well.

The changes in the structures of the variants X, Y and Z are equal. The changes are the following:

- EFS and a longer beam are added to the structures as an option (2-E → 2-E (H + a longer beam) or 2-B → 2-B(H + a longer beam))

The brackets around H and a longer beam indicate that the features are options. After the modification Working structure X_{EFS} is 1-D, 2-E (H + a longer beam), 3-B, 4-A+soft ware application, 5-B, 6-B, Structure Y_{EFS} 1-F, 2-B(H + a longer beam), 3-C, 4-A, 5-B, 6-B and Structure Z_{EFS} 1-F, 2-B(H + a longer beam), 3-D, 4-A, 5-B, 6-B. The improved structures are evaluated in Table 5.15. in the next page.

Table 5.15. *The evaluation chart of the improved structures. Evaluation is executed with an option of EFS and a longer beam.*

Evaluation criteria		**Objective parameters**		**Working structure X_{EFS}**		**Working structure Y_{EFS}**		**Working structure Z_{EFS}**	
Criterion	Weight	Parameter	Unit	Value	Weighted value	Value	Weighted value	Value	Weighted value
1	0.1	1	-	3	0.30	3	0.30	3	0.30
2	0.075	2	-	2	0.15	2	0.15	2	0.15
3	0.075	3	-	3	0.225	4	0.30	4	0.30
4	0.075	4	-	4	0.30	4	0.30	4	0.30
5	0.0375	5	-	4	0.15	4	0.15	4	0.15
6	0.0375	6	-	4	0.15	4	0.15	4	0.15
7	0.1	7	-	2	0.20	2	0.20	3	0.30
8	0.1	8	-	3	0.30	3	0.30	3	0.30
9	0.08	9	-	2	0.16	2	0.16	2	0.16
10	0.04	10	-	3	0.12	2	0.08	2	0.08
11	0.04	11	-	2	0.08	2	0.08	2	0.08
12	0.04	12	-	3	0.12	3	0.12	3	0.12
13	0.08	13	-	3	0.24	2	0.16	3	0.24
14	0.08	14	-	4	0.32	4	0.32	4	0.32
15	0.04	15	-	4	0.16	4	0.16	4	0.16
	$\sum = 1$			$\sum = 46$	$\sum = \mathbf{2.975}$	$\sum$=45	$\sum$=**2.93**	$\sum$=47	$\sum$=**3.11**

It is to be noted that all the structures after the second iteration round reach significantly lower grades than before iteration. This is due to the new demand. The addition of extendable front frame and EFS affects especially the following criteria: compact size, visibility, component costs, assembly costs, maintenance, steerability, mobility, simplicity of the structure and reliability. The option deteriorates all the concepts equally and thus it does not change their relative order of superiority.

Creating the value profiles for concepts X_2, Y_2 and Z_2 is unnecessary at this point. According to Tables 5.12. and 5.15. working structure Z/Z_{EFS} appears to be the best combination. It can’t be further improved within the limits of current demands. As mentioned after the first iteration, there might be troubles with hosing.

For reaching the highest score both without and with EFS, concept Z is chosen to be the concept output of this thesis. For a short summary, the chosen concept is presented verbally in the next page.

Concept Z:

- a rising single beam front frame
- hoses coved at the side of the front frame
- an option for EFS and a longer beam
- a boom module turned by cylinders
- zoomable jack beams

At this point, validation is executed by discussing the solution with engineering department and product line. Two service engineers were also asked for their opinion about the shape of the front frame. The validation elicited a new point of view for the shape choice. As the solution of turning the whole front frame is yielded up, the advantages of a single beam are dubious. The distinct need for turning the boom module and zoomable jack beams are also questioned. These topics are reconsidered at the third iteration round.

5.9. Iteration: round 3

As mentioned above, the third iteration round is needed because new points of view emerged during the validation. The shape, jack beams and turning the boom module are discussed at the following sub-sections.

5.9.1. The shape of the front frame

The single beam shape was questioned at the validation. Both service engineers preferred the current horseshoe shape. The arguments for the current shape were following:

- The opening holes are often drilled to the middle of the drift and the single beam would cover the needed footwall area.
- The horseshoe has better twisting tolerance than the single beam.
- The tramming position is low as the drill can be dropped between the beams.

The horseshoe shape has, however, challenges in locating the jack beams to the front carrier frame. With the current shape there is no space for the jacks between the front wheels and the front frame.

Based on the advantages and disadvantages presented above, the shape is changed to the modified horseshoe shape.

5.9.2. Jack beams

In concept Z there are two pairs of jack beams at the front end of the rig – one at the front end of the front frame and the other one in front of the front wheels. In the validation meeting a question about the need of four jacks was raised. The topic was discussed and finally the jack beams attached to the front end of the front frame were excluded from the concept. This decision also means that the front frame can't be rising.

In contrast, the jack beams in front of the front wheels were seen necessary to increase the stability of drilling and to decrease the load of the middle joint. The sufficient support can, however, be achieved without zooms, and thus the zoomable jack beams in the concept Z are changed to simple jack beams.

5.9.3. Turning the boom module

Although the ability to drill inclined fans from the cabin/canopy was an essential demand at the beginning of this thesis, the need for it is unclear at this point. For that reason, this feature is treated as an option. This thesis investigates how much higher the rig would become if the boom module was turning.

5.9.4. The final concept

After three iteration rounds the final concept for this thesis has been found. The changes described at the previous sub-sections are made to concept Z, and the final concept will be the following:

- a horseshoe front frame
- hoses coved at the side of the front frame
- jack beams in front of the front wheels
- an option for an EFS and a longer beam
- an option for a turning boom module

5.10. Firming up the selected concept

The next step in concept development is to illustrate the functionality, shape and dimensions of the final concept. Firming up the final concept consists of four main tasks that are:

1) performing the strength calculations
2) redesigning the shape of the front frame
3) illustrating the change in length of the front frame when the option of EFS is being used
4) illustrating the change in height of the rig when the option of turning boom module is being used

These four tasks are described in more detail in the following sub-sections.

5.10.1. Strength calculations

The designing begins with calculating a proper profile for the new front frame. The hoses must be located outside the beam but the bending and torsion strength must remain at least the same as in the current front frame. In this thesis only a rough calculation is executed and several simplifications are made. It is important to remember that the strengths must be investigated in detail by a FEM-analysis before making any prototypes.

As mentioned in the theory part, calculating is started by solving the section modulus. The profile width and height of the beam of the current front frame vary along the structure. The profile dimensions that are used for simplified calculation are taken from the longest straight beam of the front frame. The place of the cross-section and the profile are presented in Figure 5.16. The spacer plates are not taken into consideration in the strength calculations.

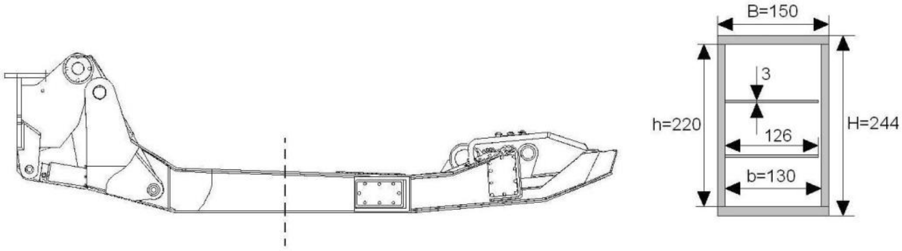


Figure 5.16. *The place of the cross-section and the enlarged profile of the current front frame used for simplified calculations. (Figure modified from: Windchill).*

According to equation [1] the section modulus of the current front frame beam is:

$$W_{z,current\ front\ frame} = \frac{150\ mm*(244\ mm)^3 - 130\ mm*(220\ mm)^3}{6*244\ mm} \approx 543 * 10^3\ mm^3. \qquad [1]$$

The maximum bending moment must be solved next. The position of the front frame during drilling is illustrated in Figure 5.17.

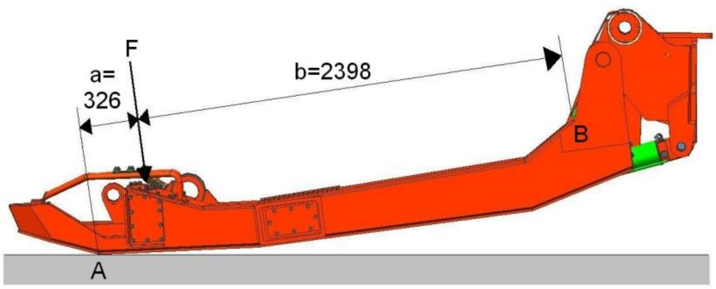


Figure 5.17. *The position of the front frame during drilling (Figure modified from: Unigraphics NX).*

In calculations, the beam is assumed to be horizontal. This assumption eases the calculations. It makes no significant error on rough calculations because the same assumptions are made to the new front frame as well. The force is directed to the middle of two fixing points of the boom module.

The force is composed of the mass of the boom, drilling module and drilling rods multiplied by the gravity of the earth. DL421s have ZR 30 boom and LFRC1600 drilling module. The weight of the boom is 2,800 kg, whereas the maximum weight of the drilling module is 3,150 kg. The drilling module can use 1,830 mm long three different sized drilling rods (diameters 39 mm, 46 mm and 52 mm) and three different sized drilling tubes (diameters 65 mm, 76 mm and 87 mm). The maximum amount of drilling rods/tubes is 29+1. (Technical Specification, DL421-15C; Technical Specification, ZR 30 boom; Technical Specification, LFRC1600) The heaviest drilling rod/tube (ST68, diameter 78 mm) weights 43.8 kg (KNP; Qiangli pneumatic tools; Atlas Copco, Bench and production drilling; Technical Specification, DL411-15; Technical Specification, DL421-15C). If the starting rod/tube is approximated to weight as much as other rods/tubes, the total weight of the drilling rods/tubes is 30×43.8 kg = 1,314 kg. Thus the force is:

$$F = (2{,}800\ kg + 3{,}150\ kg + 1{,}314\ kg) * 9{,}81\ m/s^2 \approx 71.3\ kN.$$

The bending moments at points B and F can now be calculated using equations [2] and [3].

$$M_B = -\frac{71.3*10^3\ N*326\ mm*2398\ mm}{326\ mm+2398\ mm}\left(1-\frac{2398\ mm}{2*(326\ mm+2398\ mm)}\right) \approx -11.4*10^6\ Nmm \quad [2]$$

$$M_F = -\frac{71.3*10^3 N*326\ mm*(2398\ mm)^2}{(326\ mm+2398\ mm)^2}\left(1+\frac{326\ mm}{2*(326\ mm+2398\ mm)}\right) \approx -19.1*10^6 Nmm \quad [3]$$

The bending moment is the biggest under the force. Finally, the bending stress can be solved by equation [4].

$$\sigma_t = \frac{-19.1*10^6\ Nmm}{543*10^3\ mm^3} \approx -35.1\ N/mm^2. \quad [4]$$

The twisting magnitudes are solved next. Figure 5.18. in the next page shows the moment distances and profile dimensions. Moment distance of the drilling module comes from the maximum parallel hole distance.

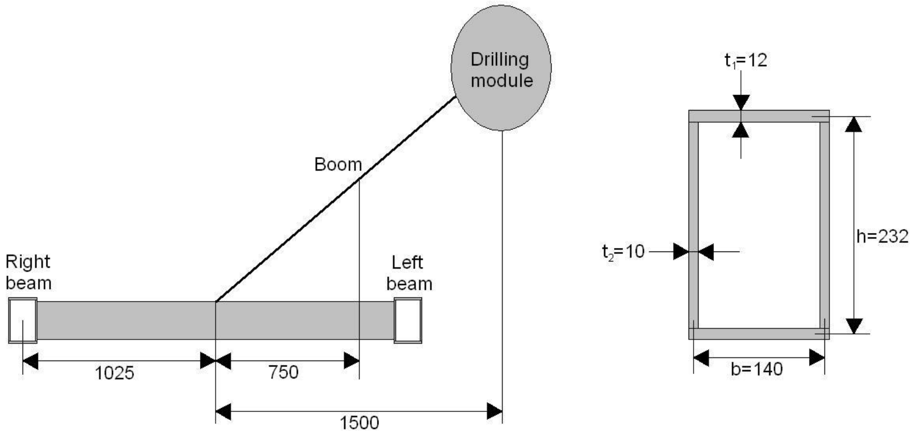


Figure 5.18. *Moment distances (left) and profile dimensions (right) (figures not in scale).*

Figure 5.18. shows the biggest possible moment that can be directed at the right beam. The moment consists of two forces. One is the force from the weight of the beam. This force is located in the middle of the beam. The other force is caused by the weight of the drilling module. The moment is solved by equation [5].

$$M = 2{,}800\ kg * 9.81\ m/s^2 * (1{,}025\ mm + 750\ mm) + (3{,}150\ kg + 1{,}314\ kg) * 9.81\ m/s^2 * (1{,}025\ mm + 1{,}500\ mm) \approx 159 * 10^6\ Nmm \qquad [5]$$

The section modulus in torsion can be solved by equation [6].

$$W_v = 2 * 140\ mm * 232\ mm * 10\ mm = 649.6 * 10^3 mm^3 \qquad [6]$$

The torsional stress can now be calculated by equation [7].

$$\tau_1 = \frac{159*10^6\ Nmm}{649.6*10^3\ mm^3} \approx 245\ N/mm^2 \qquad [7]$$

The new profile is designed to be as high as the current one. To prevent the structure to widen too much, the plates are made 2 mm thicker. Next, the width of the profile is solved to correspond with the strength of the current front frame. Figure 5.19. shows the profile.

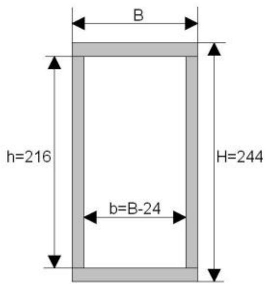


Figure 5.19. *The dimensions of the new profile.*

As neither the place nor the magnitude of the force changes from the current structure, the only factor that affects the bending stress is the section modulus. Since the wanted section modulus is solved, the width can be solved from equation [1] (b=B-24).

$$W_z = \frac{BH^3 - bh^3}{6H} \leftrightarrow B = \frac{6W_zH - 24h^3}{H^3 - h^3} = \frac{6*543*10^3\ mm^3*244\ mm - 24*(216\ mm)^3}{(244\ mm)^3 - (216\ mm)^3} \approx 124.3\ mm \quad [1]$$

The width must be calculated to stand up the torsional stress as well. Again, the width is the only changing factor when compared with the current structure. Thus, the section modulus in torsion must remain the same. Equation of the section modulus in torsion [6] is solved for b:

$$W_v = 2bht_{min} \leftrightarrow b = \frac{W_v}{2ht_{min}} = \frac{649.6*10^3\ mm^3}{2*230\ mm*12\ mm} \approx 117.7\ mm. \quad [6]$$

12 mm must be added to 117.7 mm to get the outer width of the beam. Thus the outer width of the new structure must be 129.7 mm which is rounded up to 130 mm. This is bigger of the demanded widths and for that reason the beam must be 130 mm wide.

5.10.2. The shape of the front frame

The starting point of designing the shape of the front frame is the current shape. The basic shape remains the same but redesigning is needed as the beam profile changes because of relocating the hoses. The added jack beams also demand redesigning as there is no space for them in the current front frame. Designing is executed by creating a 3D-model of the front frame.

According to the previous sub-chapter the width of the beam must be 130 mm. The hoses are located outside the beam and they must be protected from external impacts. Thus, the upper and lower plates of the front frame must be broadened. The hoses need about 20,500 mm^2 space which means approximately 95 mm in width as the inner height of the profile is 216 mm. The space is divided into three boxes by thick plates. The open side of the profile is covered with a thick plate to protect the hoses. A proposal for the profile of the new front frame is presented in Figure 5.20. in the next page. In Figure 5.20. the places of the welds are marked with orange color. The welds are not dimensioned but shown only to illustrate the manufacturing principles. According to Figure 5.20. the profile is first welded for the shape of an I-beam and then the other side is closed up.

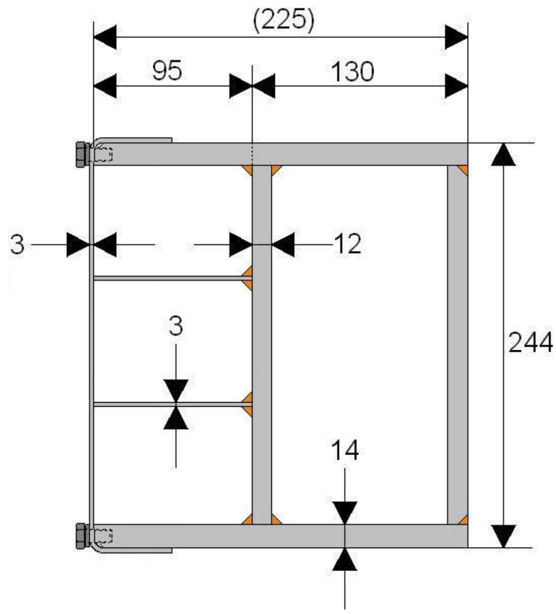


Figure 5.20. *A proposal for the beam profile of the new front frame.*

A proposal for the shape and dimensions of the new front frame is presented in Figure 5.21. The shape from the side can be seen in Figure 5.22. In Figure 5.21. the front frame and the front jack beams are presented from above. Hoses are illustrated by two pipes at the right side beam. The covers are shown in the right beam only.

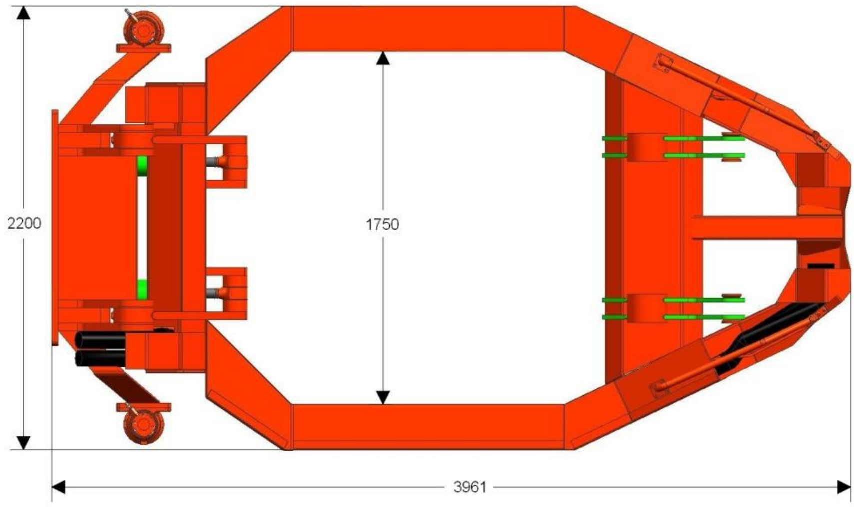


Figure 5.21. *The shape and dimensions of the proposal of the new front frame.*

Figure 5.22 in the next page shows the front part of the rig in the drilling position. The boom and the drilling module in Figures 5.22. and 5.23. are not exactly mated but set ocularly and for that reason the drawings should not be used in any specification sheets.

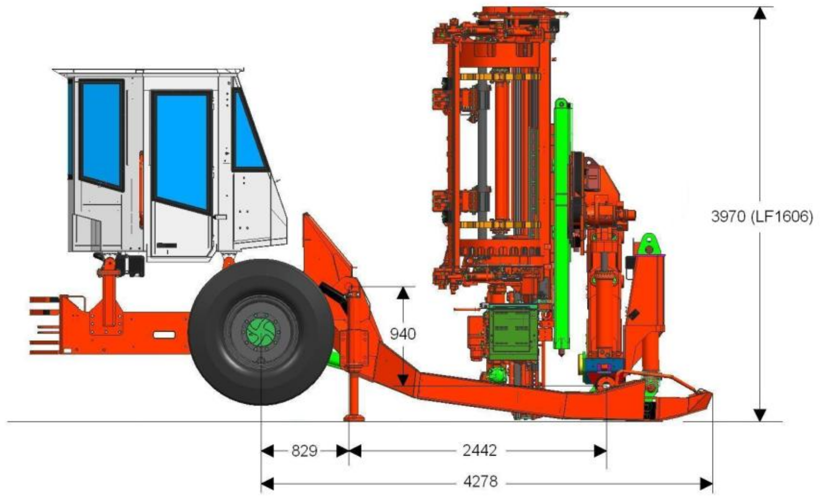


Figure 5.22. *The shape and dimensions of the proposal of the new front frame in the drilling position.*

Figure 5.23. below illustrates the tramming position of the drill. According to Technical Specification (DL421-15C) the total tramming length of DL421 is 3,280 mm + 3,530 mm + *the distance from the front wheel to the front end of the rig.* Thus the tramming length with the suggested new front frame is 11,220 mm.

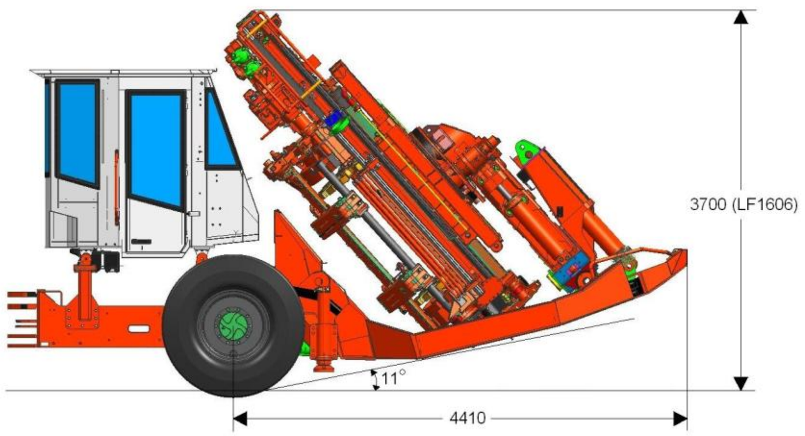


Figure 5.23. *The shape and dimensions of the proposal of the new front frame in the tramming position.*

As the tramming length does not change significantly, the turning radiuses can be assumed to remain the same as in the current DL421. Figure 5.24. in the next page shows, how the rig with the proposed front frame fits into an L-turning with the dimensions of the current rig.

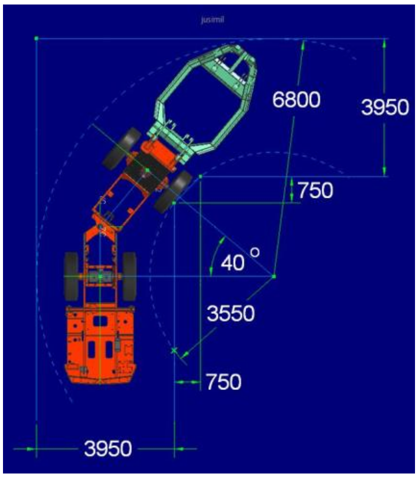


Figure 5.24. The proposed version in an L-turning with the dimensions of the current rig (Figure modified from image created by Jukka Similä).

5.10.3. Extended front frame

The drilling angles must remain the same as in the version without the EFS, and thus the drilling module must stay still. For that reason an EFS can be added to the structure only if the front frame is extended. The vertical distance between the fixing points must increase by 850 mm which is the length the EFS takes. At the same time, both drilling and tramming lengths increase. Figure 5.25. shows the extended front frame. The dimensions are rounded to an accuracy of 10 mm.

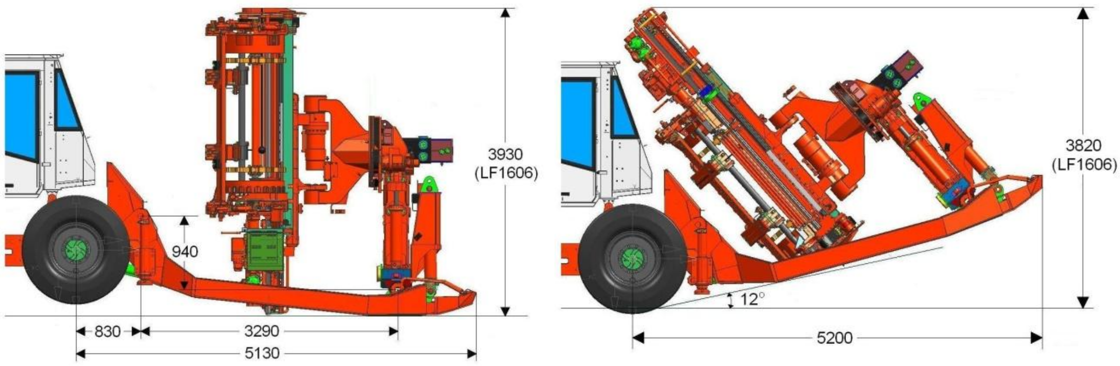


Figure 5.25. The extended front frame (dimensions rounded to the closest 10 mm).

To constrict the increase of tramming length, the angle between the ground and the lowest point of the front frame is set to 12° instead of 11° of the normal version. Already with an angle of 11°, the height of the rig exceeds 3,700 mm. Thus the rig would not fit into current tunnels in regard to the height with the current angle. According to Figures 5.23. and 5.25. the tramming length grows by almost 800 mm (from 4,410 mm to 5,200 mm) and the height by 120 mm (from 3,700 mm to 3,820 mm).

The extended front frame affects the turning angles and the stability of the rig. The turning angles are presented in Figure 5.26. in the next page and the stability is inspected in sub-section 5.10.5.

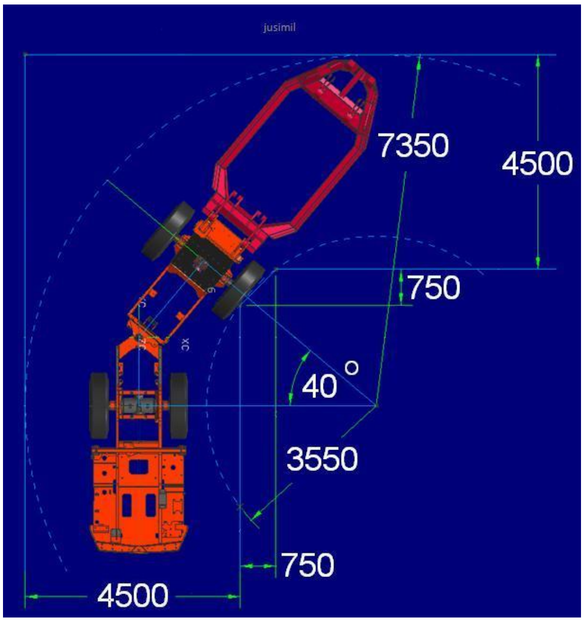


__Figure 5.26.__ The turning radiuses of the extended version (Figure modified from an image created by Jukka Similä).

Figure 5.26. shows that if the inner turning radius is remained the same as in the current version (see Figure 4.10 in page 39), the outer radius and at the same time the width of the tunnel grows by 550 mm (from 6,800 mm to 7,350 mm and from 3,950 mm to 4,500 mm).

According to the dimensions in Figures 5.25. and 5.26., adding the EFS to the structure increases the outer dimensions and the outer turning angle of the rig significantly. Thus, adding the EFS to DL421 can be realized only if the growth of the rig and the tunnel is accepted.

5.10.4. Turning boom module

If the boom is turned, an extra part must be put under the cross beam to enable turning. The suggestive picture of the cross-section of the structure and the profile of the extra part is shown in Figure 5.27. This thesis presents only one way to turn the cross beam but it is important to keep in mind that the structure presented below can be realized in many other ways as well.

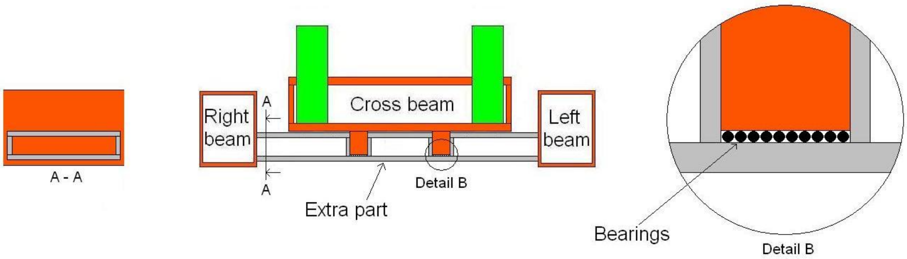


__Figure 5.27.__ The cross-section of the structure and the profile of the extra part (Figure not in scale).

The extra part could have for example two curved holes, into which the arched glide parts at the bottom of the cross beam dig. Figure 5.28. is presented to give the reader an idea of the top view of the extra part.

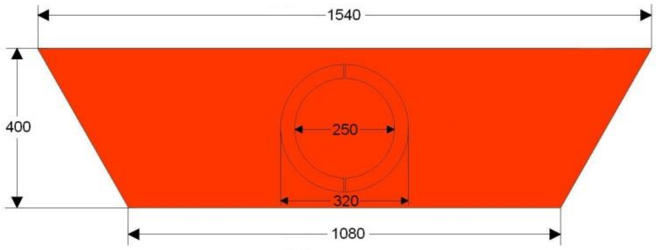


Figure 5.28. *A suggestive top view of the extra part (dimensions rounded to the closest 10 mm).*

The extra part raises the boom module by approximately 100 mm. The effects to the outer dimensions are shown in Figure 5.29. The height increases both in the drilling and tramming position by approximately 100 mm. Thus the rig with the extra part does not fit into the tunnels, the current rig fits in. Raising the boom module does not affect other dimensions.

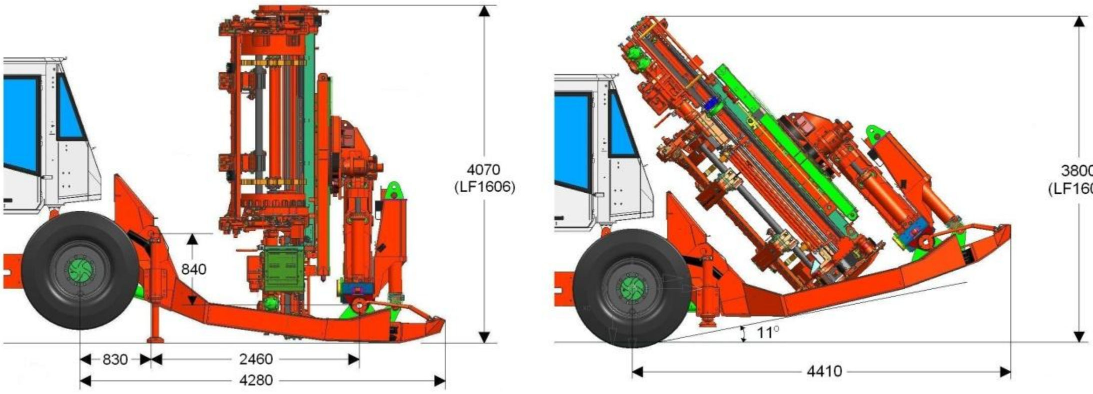


Figure 5.29. *The front frame with an extra part under the boom module.*

Thus, it can be said that the extra part can added only if the increase in height in accepted.

5.10.5. Stability inspection of the versions

The stability inspection is performed by investigating the place of the centre of gravity. The centre of gravity of the front frame and its front support is solved by a 3D design program and the places of different versions are shown in Figures 5.30.-5.33. As the new models are just rough modellings and the parts are set on their places ocularly, the dimensions are rounded; weights by the accuracy of 50 kg and distances by the accuracy of 5 mm.

Figure 5.30. illustrates the place of gravity of the current version. The weight of the structure without welds, screws and washers is rounded to 2,100 kg.

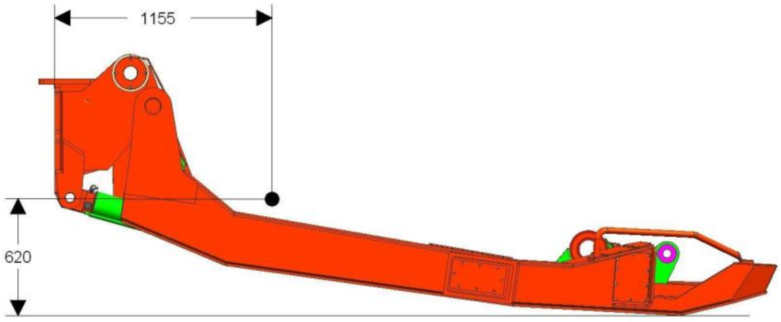


Figure 5.30. *The centre of gravity of the current front frame assembly (Figure modified from: Unigraphics NX).*

Figure 5.31. shows the centre of gravity of the proposed version. The weight of the structure without welds, screws and washers is rounded to 2,400 kg. The jack beam assemblies cause the horizontal movement of the center of gravity; it moves 40 mm closer to the interface when compared with the current version. The jack beams together with the shape of the front frame lower the center of gravity in respect of the ground level by 35 mm. As the center of gravity comes closer to the front axle and the ground, the stability of the rig should not be a problem. It is, however, important to remember that the stability inspections performed in this thesis are highly superficial and more detailed calculations are needed before starting manufacturing.

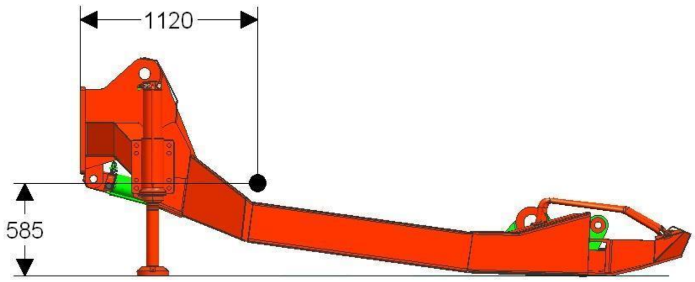


Figure 5.31. *The centre of gravity of the proposed front frame assembly.*

Figure 5.32. in the next page shows the centre of gravity for the extended front frame assembly. The weight of that version is 2,550 kg without welds, screws and washers. The vertical place of the centre of gravity lowers by 55 mm but the horizontal distance increases by 255 mm in comparison with the current version. This increase in the horizontal distance causes troubles for the stability of the rig, especially in tramming. In addition, the weight of the EFS is not considered in the calculations. Thus, according to the stability inspection, the extended front frame is unacceptable.

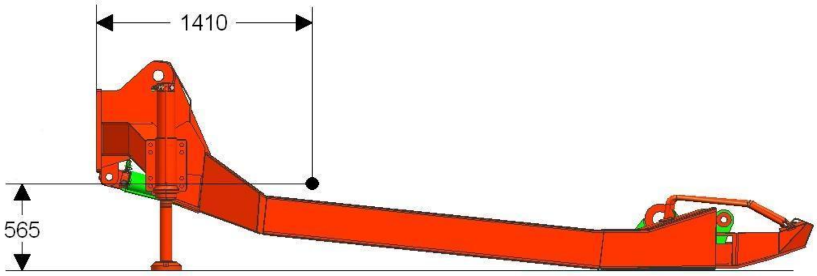


Figure 5.32. *The centre of gravity of the extended front frame assembly.*

The centre of gravity of the version with the turned boom module is illustrated in Figure 5.33. The weight of the structure without welds, screws and washers is approximately 2,550 kg. The extra part under the boom module is extremely simplified and for that reason the weight is only an approximation. The extra part lowers the centre of gravity point by 65 mm in comparison to the current front frame assembly. At the same time the extra part moves the centre of gravity 90 mm further from the interface. The increase of the vertical distance may cause troubles in stability. The decision whether the extra part can be used or not needs more stability calculations.

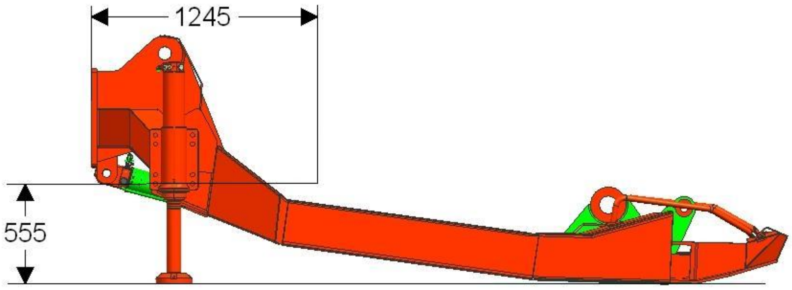


Figure 5.33. *The centre of gravity of the version with the turning boom module.*

As a summary, after a superficial inspection, stability seems to be good in the proposed version but a problem in the extended and turning versions.

5.10.6. Decisions

According to the dimensions and stability inspection, the proposed front frame illustrated in Figures 5.21.-5.23. is the output of this thesis.

Because of the increasing outer dimensions and insecure stability, the features that enable drilling inclined fans (the turning boom module) and getting close to the wall (the extended front frame) can't be added to DL421.

5.10.7. Verification

At this point, it is important to check whether the proposed front frame fulfills the demands of the requirements list (see Table 4.6. in pages 47-48). The verification will be executed by going through the requirements point by point.

Geometry

The tramming length of the rig with the proposed front frame is 11,220 mm. The demand for the tramming length is equal or less than 11,250 mm and thus the length demand have been fulfilled.

According to Figure 5.24. the inner turning radius is approximately 3,550 mm and the outer turning radius 6,800 mm. With these values the verification is passed.

Width of the proposed front frame with the covers is 2,206 mm and goes under the demand of 2,290 mm. The demand for the tramming height is also passed as the as the height of the proposed version remains the same as in the current rig.

Kinematics

The new shape may slightly affect back underhand and front overhand drilling angles but the verification can still be considered as passed for the kinematics part.

Drilling area

The drilling module and the boom remain the same as in the current DL421 and thus the drilling area demands are fulfilled. According to Sub-section 5.10.4. the wish of ability to drill inclined fans can't be fulfilled because of size and stability problems.

Forces

According to Unigraphics NX the mass of the front frame is approximately 2,400 kg without any screws, welds etc. This is 300 kg more than it should be according to the requirements list. The growth of the front frame assembly is inevitable because of broadened profile and added jack beams. The profile alone increases the mass per unit of length as follows (for the profiles, see Figure 5.16. in page 80 and Figure 5.20. in page 84):

$$\begin{aligned}\Delta A = A_{new} - A_{current} \\ &\approx (225\,mm * 14\,mm * 2 + 216\,mm * 12\,mm * 2 + 95\,mm * 3\,mm \\ &* 2 + 50\,mm * 3\,mm * 2 + 244\,mm * 3\,mm) \\ &- (150\,mm * 12\,mm * 2 + 220\,mm * 10\,mm * 2 + 126\,mm * 3\,mm \\ &* 2) = 13{,}086\,mm^2 - 8{,}765\,mm^2 = 4{,}321\,mm^2\end{aligned}$$

$$\frac{\Delta mass}{L} = \frac{\Delta V * \rho}{L} = \frac{\Delta A * L\rho}{L} = \Delta A * \rho = 4{,}321\,mm^2 * 0.0000078\ kg/mm^3 \approx 0.0337\,kg/mm = 33.7\ kg/m,$$

where A is the area of the profile, L length, V volume and ρ density of steel (according to Valtanen 2012, p. 310 the density of steel is around 7.8 kg/dm^3).

The strength of the structure is calculated roughly to fulfill the demand of sufficient strength. It is, however, important to check the strength by FEM before starting the exact design.

Material

The material remains the same as in the current rigs and thus the material part of the requirements list is passed. The thicker plates at the side beams even improve the corrosion tolerance.

Safety

In the proposed new front frame the driller is under the roof during drilling. The drilling stability is improved by the jack beams and the tramming stability will not remarkably change. There is no significant change in the tramming and drilling stabilities and thus the verification of the safety part can be considered as passed.

Ergonomic

The new shape does not outstandingly affect the ergonomic environment of the operator and the demand of the ergonomic operator environment is passed.

Production

The beams in the proposed version are fairly simple to manufacture. First, the beam is welded to the shape of an I-beam and then the plate is welded to the other side. The wish of easy manufacturing is fulfilled.

Maintenance

Because of the location of the hoses the proposed front frame is easier to maintenance than the current version. The covers are easy to detach and fasten. The new structure has no significant effect on the maintenance interval. The releasable covers also ease cleaning as they can be washed separately. Thus the maintenance wishes are fulfilled.

Costs

The proposed front frame has no remarkable difference in manufacturing costs when compared with the current front frame. The verification of the costs part can be considered as passed.

Regulation

The solution fulfills the current standards and directives in the whole world but as the integration of the rigs was discovered impossible the situation in the future was not improved. Thus the demand of the regulation was fulfilled but the wish was not.

Schedule
Concept design was completed on 23 April 2012 and the schedule verification is passed.

As a summary, the verification is passed under all the factors but the weight. The increase in weight is inevitable and must be accepted if the hoses are to be located outside the closed beams. In further design the increase in weight must be considered when choosing the rear axle and the rear wheels.

6. CONCLUSIONS

The goal of this thesis was to improve the front part of Sandvik's frame model of the production drill rigs. Model DL421 was chosen to be the model on the table. The first goal was to investigate whether two features could be integrated to DL421. These features were getting the drill close to a side wall of the drift in a vertical position and ability to drill inclined fans. The other goal was to redesign the front frame of DL421 to ease the maintenance of the hoses and to improve the drilling stability of the rig.

The concept development process was carried out by applying Pahl et al.'s and Ulrich's & Eppinger's product design methodologies. The solution was found after three iteration rounds.

According to the research, getting the drill close to the side wall in the model DL421 by adding an EFS to the structure is possible only if the front frame is extended by approximately 850mm. The extended front frame needs a bigger tunnel to tram in and have troubles with the stability. For that reason, adding the EFS to DL421 was seen impossible to realize.

The concept development process also showed that adding a feature that would make inclined fans possible to be drilled with a DL421 rig was problematic. Adding an extra part under the drilling module to turn the drill increases the height of the rig. Thus, the rig would not fit into the tunnels the current rigs fit in. The stability of the rig with the extra part was also found problematic. Therefore, adding the extra part was also seen impossible to realize.

As a result, the basic shape of the front frame of DL421 remained a horseshoe. Adding the jack beams to the front carrier frame to improve the drilling stability of the rig and locating the hoses outside the closed beams to ease maintenance caused some changes to the shape of the current front frame. The front frame was narrowed at the rear end to create the space for the jack beams. Locating the hoses outside the closed beams, in turn, caused the widening of the side beams from 150 mm to 225 mm. The outer dimensions of the front frame remained the same as in the current DL421. As the changes to the shape and structure are fairly easy to realize, the result can be considered successful.

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APPENDIX 1: A SELECTION CHART BY PAHL ET AL.

Table A1: *An example of a selection chart (table modified from source: Pahl et al. 2007, p. 187).*

Company								SELECTION CHART for	Part: Page:
Solution variants evaluated by SELECTION CRITERIA (+) Yes (–) No (?) Lack of information (!) Check requirements list								DECISION Mark solution variants (+) Pursue solution (–) Eliminate solution (?) Collect information (re-evaluate solution) (!) Check requirements list for changes	
Solution variant	A Compatibility assured	B Fulfills demand of requirements list	C Realizable in principle	D Within permissible costs	E Incorporates direct safety measures	F Preferred by designer’s company	G	Remarks (Indications, Reasons)	DECISION
A1	+	+	–					…	–
A2	+	+						…	+
A3	+	+	+	+	+	+		…	+
B1	?							…	?
B2	+	!						…	!
B3	+	+	+					…	+
C1	+	+	+	+				…	+
C2	+	-						…	–
C3	+	+	?					…	?
Date:				Initials:					

APPENDIX 2: A COMPATIBILITY MATRIX BY DREIBHOLZ (SEE PAHL)

Table A2. *An example of a compatibility matrix (table modified from: Dreibholz 1975, see Pahl et al. 2007, p. 105).*

Subfunctions \ Solutions		1	2	3
A	Subfunction_1	No (reason)	Yes	Yes
B	Subfunction_2	Yes	Yes (if)	If…
C	Subfunction_3	Yes	No (reason)	Yes

very difficult to realize

usable in certain situations

APPENDIX 3: POINT RANGES AND PARAMETER MAGNITUDES

Table A3. *Point ranges of Cost-Benefit Analysis and VDI 2225 (table modified from source: Pahl et al. 2007, p. 115).*

<table>
<tr><th colspan="2">Cost-Benefit Analysis</th><th colspan="2">VDI 2225</th></tr>
<tr><th>Points</th><th>Meaning</th><th>Points</th><th>Meaning</th></tr>
<tr><td>0</td><td>absolutely useless</td><td rowspan="2">0</td><td rowspan="2">unsatisfactory</td></tr>
<tr><td>1</td><td>very inadequate</td></tr>
<tr><td>2</td><td>weak</td><td rowspan="2">1</td><td rowspan="2">just tolerable</td></tr>
<tr><td>3</td><td>tolerable</td></tr>
<tr><td>4</td><td>adequate</td><td rowspan="2">2</td><td rowspan="2">adequate</td></tr>
<tr><td>5</td><td>satisfactory</td></tr>
<tr><td>6</td><td>good with few drawbacks</td><td rowspan="2">3</td><td rowspan="2">good</td></tr>
<tr><td>7</td><td>good</td></tr>
<tr><td>8</td><td>very good</td><td rowspan="3">4</td><td rowspan="3">very good (ideal)</td></tr>
<tr><td>9</td><td>exceeding the requirement</td></tr>
<tr><td>10</td><td>ideal</td></tr>
</table>

Table A4. *An example of a chart notifying parameter magnitudes (table modified from source: Pahl et al. 2007, p. 116)*

<table>
<tr><th colspan="2">Points</th><th colspan="3">Parameter magnitudes</th></tr>
<tr><th>Cost-Benefit Analysis</th><th>VDI 2225</th><th>Mass kg</th><th>Safety</th><th>…</th></tr>
<tr><td>0</td><td rowspan="2">0</td><td>200</td><td rowspan="2">extremely unsafe</td><td></td></tr>
<tr><td>1</td><td>190</td><td></td></tr>
<tr><td>2</td><td rowspan="2">1</td><td>180</td><td rowspan="2">unsafe</td><td></td></tr>
<tr><td>3</td><td>170</td><td></td></tr>
<tr><td>4</td><td rowspan="2">2</td><td>160</td><td rowspan="2">average</td><td></td></tr>
<tr><td>5</td><td>150</td><td></td></tr>
<tr><td>6</td><td rowspan="2">3</td><td>140</td><td rowspan="2">safe</td><td></td></tr>
<tr><td>7</td><td>130</td><td></td></tr>
<tr><td>8</td><td rowspan="3">4</td><td>120</td><td rowspan="3">extremely safe</td><td></td></tr>
<tr><td>9</td><td>110</td><td></td></tr>
<tr><td>10</td><td>100</td><td></td></tr>
</table>

APPENDIX 4: CHECK LIST

Table A5. *A check list for establishing demands and wishes (Pahl et. al 2007, p. 149).*

Main headings	**Examples**
Geometry	Size, height, breadth, length, diameter, space requirement, number, arrangement, connection, extension
Kinematics	Type of motion, direction of motion, velocity, acceleration
Forces	Direction of force, magnitude of force, frequency, weight, load, deformation, stiffness, elasticity, inertia forces, resonance
Energy	Output, efficiency, loss, friction, ventilation, state, pressure, temperature, heating, cooling, supply, storage, capacity, conversion.
Material	Flow and transport of materials. Physical and chemical properties of the initial and final product, auxiliary materials, prescribed materials (food regulations etc)
Signals	Inputs and outputs, form, display, control equipment.
Safety	Direct safety systems, operational and environmental safety.
Ergonomics	Man-machine relationship, type of operation, operating height, clarity of layout, sitting comfort, lighting, shape compatibility.
Production	Factory limitations, maximum possible dimensions, preferred production methods, means of production, achievable quality and tolerances, wastage.
Quality control	Possibilities of testing and measuring, application of special regulations and standards.
Assembly	Special regulations, installation, siting, foundations
Transport	Limitations due to lifting gear, clearance, means of transport (height and weight), nature and conditions of dispatch.
Operation	Quietness, wear, special uses, marketing area, destination (for example, sulphurous atmosphere, tropical conditions).
Maintenance	Servicing intervals (if any), inspection, exchange and repair, painting, cleaning.
Recycling	Reuse, reprocessing, waste disposal, storage
Costs	Maximum permission manufacturing costs, cost of tooling, investment and depreciation.
Schedules	End date of development, project planning and control, delivery date

APPENDIX 5: THE FIRST VERSION OF THE REQUIREMENTS LIST

Table A6. *The original requirements list.*

Sandvik Mining		Requirements list for a boom module	Issued on: 24 November, 2011 Page:1/3
Dates of changes	Demand /Wish	Requirements	Responsible
		1. Geometry	Aino-Maija Mylläri
	D	• Tramming length ≤ 11.25 m	
	W	• Tramming length ≤ 10.5 m	
	D	• Distance from the rear axle to the front end of the rig ≤ 4 m	
	W	• Distance from the rear axle to the front end of the rig ≤ 3.5 m	
	D	• Width of the front frame ≤ 2.29 m	
	W	• Width of the front frame = 2.2 m	
	D	• Tramming height ≤ 3.7 m	
	W	• Tramming height = 3.2 m	
	D	• Drill faces the cabin/canopy	
	D	• Interface to the front carrier frame: horizontal distance of the outermost holes = 1,090 mm	
	D	• Interface to the front carrier frame: vertical distance of the outermost holes = 475 mm	
	D	• Interface to the front carrier frame: amount of holes (horizontal × vertical) = 11 × 4	
	D	• Interface to the front carrier frame: diameter of the holes = 27 mm	
	D	• Interface to the boom: diameter of the bigger holes = 120 mm	
	D	• Interface to the boom, diameter of the smaller holes = 75 mm	
	D	• Interface to the boom: horizontal distance of bigger holes = 650 mm	
	D	• Interface to the boom: horizontal distance of smaller holes = 736 mm	
		Replaces issue of -	

Sandvik Mining		**Requirements list** **for a boom module**	**Issued on:** **24 November, 2011** **Page:2/3**
Dates of changes	Demand /Wish	Requirements	Responsible
	D	• Interface to the boom: depth of the bigger holes (from outer faces) = 150 mm	Aino-Maija Mylläri
	D	• Interface to the boom, depth of the smaller holes (from inner faces) = 64 mm	
	D	• Extendable front frame	
		2. Kinematics	
	W	• Turning angle of the front frame = 10…35°	
	D	• Underhand drilling angles, front/back ≥ 30/30°	
	W	• Underhand drilling angles, front/back ≥ 30/45°	
	D	• Overhand drilling angles, front/back ≥ 45/30°	
		3. Drilling area	
	D	• Maximum parallel coverage = 3 m	
	D	• Maximum coverage width = 5.4 m	
	W	• Maximum coverage width > 5.4 m	
	D	• Maximum coverage height = 4.67 m	
	W	• Maximum coverage height > 4.67 m	
		3. Forces	
	D	• Weight of the front frame ≤ 2,200 kg	
	D	• Sufficient strength of the structure of the front frame	
	D	• Ability to bear resonance	
		4. Material	
	D	• Suitable in temperature range -40…+60°C	
	D	• Corrosion tolerant	
		5. Safety	
	D	• Operator under a roof during drilling	
	D	• Stable structure	
	W	• Good tramming visibility	
	D	• Satisfactory tramming visibility	
	D	• Good drilling visibility	
		Replaces issue of -	

<table>
<tr><td colspan="2">Sandvik Mining</td><td>Requirements list
for a boom module</td><td>Issued on:
24 November, 2011
Page:3/3</td></tr>
<tr><td>Dates of changes</td><td>Demand /Wish</td><td>Requirements</td><td>Responsible</td></tr>
<tr><td></td><td>
W

W

W
W
W
W

W

D

W

D

W</td><td>6. Ergonomics
• Clear maneuverability of the front frame

7. Production
Easy to manufacture

8. Maintenance
• Easy to maintain
• Long time between regular maintenances
• Easy to clean
• Minor need of spare parts

9. Costs
• Profitable to manufacture

10. Legislation
• Fulfillment of current legislations in the whole world
• Fulfillment of impending legislation in the whole world

11. Schedules
• Concept development ready by May 31, 2012
• Concept development ready by March 30, 2012</td><td>Aino-Maija Mylläri</td></tr>
<tr><td colspan="2"></td><td>Replaces issue of -</td><td></td></tr>
</table>

APPENDIX 6: INTERVIEW OF A DRILLER

Mine visit in Pyhäsalmi, 29 November, 2011.
Interviewee: driller Kari Kumpumäki

Mr. Kumpumäki was interviewed about the frame model of the production drill rigs. In his work in Pyhäsalmi Mine Mr. Kumpumäki operates an older revision of DL421. The answers are not word-for-word as the interview was not taped. Only the answers concerning the front frame are presented in this paper.

What is favorable in the rig? Why is this rig better than the others?

- No experience of other rigs.

What is unfavorable?

- Corrosion decreases the strength of the front frame. The front frame was about to snap and it had to be strengthened.
- Movements of the boom are inflexible.

Desirable features:

- Wider drilling angles for underhand holes, particularly to the front. This is important as most of the holes are drilled underhand in Pyhäsalmi Mine.
- An assertive structure

How is the stability of the rig during drilling or moving the boom? How could it be improved?

- Sometimes stability is poor and it could be improved by adding jack beams with zooms to the front of the rig.

What is hosing like in the rig?

- It is problematic because maintenance and changing the hoses is difficult.
- Hoses should be in sight and there should be more joints in them.
- Hoses could possibly be located to the side(s) of an I-beam.

If inclined fans were possible, would there be use for it?

- Definitely yes.

Other notices:

- A structure of one beam (like in Atlas Copco's rigs) could be a suitable solution.
- Cables and electronic components should be well-sheltered.

APPENDIX 7: PARTICIPANTS OF THE TUPLATIIMI MEETING

The following list includes the names of the participants of the Tuplatiimi meeting on 20 December, 2011 in alphabetical order:

Hakala, Markus
Järventausta, Sami
Kansola, Martti
Mylläri, Aino-Maija
Piipponen, Juha
Pirttilahti, Juha
Pohjola, Pasi
Pulkkinen, Henry
Vuojela, Pasi